PREDICTING THE EFFECT OF FOREST COVER CHANGES ON FLOW DURATION CURVES

Alice Elizabeth Brown

Submitted in total fulfilment of the requirements of the degree of Doctor of Philosophy

October 2008

Department of Civil and Environmental Engineering
The University of Melbourne
Abstract

Forests use more water than grass. This statement has implications for how we manage land-use change and water resources. This thesis uses paired catchment studies to understand how alterations in forest cover affect streamflow. This understanding is used to develop a model for predicting how a catchment’s flow duration curve (FDC) will change following a change in forest cover. The model has been tested on catchments undergoing a permanent change in forest cover and has proven to be robust.

Paired catchment studies have been widely used as a means of determining the magnitude of water yield changes resulting from changes in vegetation. This thesis reviews the use of paired catchment studies for determining the changes in water yield at various time scales resulting from permanent changes in vegetation. Comparisons are made between paired catchment results and a mean annual water balance model and show good agreement between the two methodologies. Four types of paired catchment studies are considered in the thesis and the results highlight the potential underestimation of streamflow changes if regrowth experiments are used to predict the impact of permanent alterations to forest cover. The literature review summarises seasonal changes in water yield, highlights the proportionally larger impact on low flows, and demonstrates the potential for using FDCs to gain a greater understanding of the impact of vegetation on the distribution of daily flows.

The literature review highlighted that different methods used to assess the impact of forest cover make general conclusions difficult to draw. A consistent analysis of data from 46 paired catchment studies assessed annual streamflow and FDCs. The results indicate that it takes between 8 and 25 years for a catchment to reach a new equilibrium following a permanent change in forest cover. Analysis of the FDCs in the afforestation and deforestation experiments showed that the responses could be grouped into three categories. These are: (1) catchments that a change from perennial to ephemeral, or ephemeral catchments have a change in the number of zero flow days, (2) perennial catchments that have a proportionally larger reduction in low flows compared to high flow, and, (3) perennial catchments have a uniform reduction in all flow percentiles.

The analysis of paired catchment studies demonstrated that FDCs could alter in different ways following a change in forest cover. To develop a predictive methodology for adjusting a catchment’s FDC for forest cover change a five-parameter model was
developed to describe the shape of any FDC. The model proved to provide good predictions for all flow percentiles. To adjust the shape of the FDC for change in forest cover, the parameters of the FDC model for current vegetation conditions are adjusted based on an estimated change in mean annual streamflow. The linkage between the estimated change in mean annual streamflow and the parameters of the FDC model comes from the knowledge that the area under the FDC must be equal to the mean annual streamflow. The FDC adjustment methodology was tested on 17 experimental catchments that have undergone large percentage changes in forest cover and has proved to be a robust procedure. To demonstrate the applicability of this methodology to real world catchments, the method was applied to sub-catchments of the Murrumbidgee River Basin, Australia for two potential forest-cover change scenarios. The adjusted FDCs were used to develop new input time series to the daily river planning model. This allows an assessment of the impacts of forest cover change on water uses at both a local and regional scale.
Declaration
This is to certify that
(i) the thesis comprises only my original work towards the PhD except
where indicated in the Preface*,
(ii) due acknowledgement has been made in the text to all other material
used,
(iii) the thesis is less than 100,000 words in length, exclusive of tables,
maps, bibliographies and appendices.

Alice Elizabeth Brown

Preface
Two substantially unchanged multi-author papers are included in this thesis as Chapter
2 and Chapter 7.

The co-authors of the paper presented in Chapter 2 are my supervisors in this thesis
who provided guidance in this research.

The co-authors of the paper presented in Chapter 7 undertook the following work on
the paper:

• Geoff Podger (CSIRO) provided guidance relating to the interpretation of the
results from the River System model.

• Andrew Davidson (New South Wales Department of Water and Energy),
undertook the model runs for the base case and the two forest cover change
scenarios with the Integrated Quantity and Quality Model (IQQM).

• Trevor Dowling (CSIRO) undertook the GIS work to assist in the development
of the scenarios and preparation of figures.

• Lu Zhang (CSIRO) as one of my supervisors provided guidance in the research
undertaken.
Acknowledgments

Many people have provided me with a lot of encouragement during the completion of this thesis. What follows is a short list of people and organisations that have provided help and data, without which this research would not have been possible. Apologies to anyone I may have omitted.

My supervisors, Lu Zhang, Andrew Western, and Tom McMahon, provided invaluable advice and guidance during the undertaking of the research and writing of this thesis. In the last few years, Lu and Andrew have been fantastic in their persistent and timely encouragement to ensure the completion of this thesis.

The following people and organisations provided the data used in this thesis:

- CSIR South Africa provided data for the South African experimental catchments.
- Thiess Environmental Services provided data for the Pine Creek catchment.
- The Department of Environment, Western Australia, provided data for the Collie River catchments.
- Barry Fahey from Landcare Research, New Zealand, provided data from the Glendhu Catchments.
- Ian Watson from Melbourne Water, provided data for the Melbourne Water catchments.
- State Forests New South Wales provided data for Geebung Creek, Germans Creek, and Stringybark Creek catchments.
- Pat Lane provided data for the Wicksend and Willbob catchments.
- CSIRO (Klaus Hickel and Sue Vink) provided experimental data for Red Hill.
- The Centre for Ecology and Hydrology, United Kingdom, provide data for the UK catchments.
- Data sets for HJ Andrews, Coyote Creek, and Fox Creek were provided by the Forest Science Data Bank, a partnership between the Department of Forest Science, Oregon State University, and the U.S. Forest Service Pacific Northwest Research Station, Corvallis, Oregon. Funding for these data was provided by the Long-Term Ecological Research (LTER) program and other National Science Foundation programs (NSF), Oregon State University, and

A large number of people have provided useful comment on various chapters of this thesis. In particular, I would like to acknowledge:

- Rob Vertessy, Sandra Roberts, Peter Richardson, Francis Chiew, and an anonymous reviewer for their helpful comments on the initial literature review and the subsequent paper presented in Chapter 2.

- Geoff Podger for his useful advice during the development and testing of the work presented in Chapter 6 and the subsequent application of this work (Chapter 7) in the Murrumbidgee River.

- Andrew Davidson and Trevor Dowling without whom the application in the Murrumbidgee River (Chapter 7) would not have been possible.

To everyone at CSIRO Land and Water who have provided me with advice during the course of this research, I would particularly like to acknowledge Pat Lane, Richard Silberstein, Klaus Hickel, and Peter Hairsine for their useful conversations and for providing me with the opportunity to undertake work outside the bounds of this thesis.

Finally, I would like to thank my friends and family for their continual support particularly my parents, Donald and Terry Best. Lastly, I would like to thank my husband, Andrew, for all his love, support, and his continual belief that I would complete my thesis, and my two little boys Thomas, who has provided lots of love, hugs, and distraction in the last two years, and Daniel, whose first smiles corresponded with me starting on my thesis corrections.
## Table of Contents

Abstract .................................................................................................................. i
Declaration .......................................................................................................... iii
Acknowledgments ............................................................................................... v
Table of Contents ................................................................................................. vii
Table of Figures ................................................................................................... xi
Table of Tables ..................................................................................................... xvii

### CHAPTER 1 Introduction
1.1 Thesis aims and objectives ........................................................................... 2
1.2 Paired catchment studies ............................................................................ 3
1.3 Flow Duration Curves ................................................................................. 3
1.4 Modelling approach ..................................................................................... 5
1.5 Thesis Outline ............................................................................................... 6

### CHAPTER 2 Literature Review
2.1 Introduction .................................................................................................. 9
2.2 Paired catchment studies ............................................................................ 10
2.3 Mean annual water yield ........................................................................... 13
2.4 Annual water yield response time ............................................................... 21
2.5 Seasonal water yield .................................................................................. 27
2.6 Flow duration curves .................................................................................. 31
2.7 Discussion .................................................................................................... 37
2.8 Summary ....................................................................................................... 39

### CHAPTER 3 Data Description
3.1 Introduction .................................................................................................. 43
3.2 Types of experimental catchments ............................................................... 43
3.3 Brief Description of experimental catchments ............................................. 44
3.3.1 Regrowth experiments .......................................................................... 45
3.3.2 Forest conversion experiments ............................................................... 51
3.3.3 Deforestation experiments ..................................................................... 52
3.3.4 Afforestation experiments ..................................................................... 54
3.3.5 Other experimental studies .................................................................... 58
3.4 Rainfall Data ................................................................................................ 59
3.5 Potential Evapotranspiration Data (PET) .................................................... 59
3.6 Conclusion ..................................................................................................... 59

### CHAPTER 4 Impact of forest cover changes on annual streamflow and flow duration curves
4.1 Introduction .................................................................................................. 61
4.2 Data .............................................................................................................. 62
4.3 Methodology ................................................................................................. 63
4.3.1 Estimating the change in annual streamflow ......................................... 63
4.3.2 Fitting response curves to annual streamflow results ............................. 65
4.3.3 Calculating changes in Flow Duration Curves ....................................... 66
4.4 Results – Annual Water Yield ..................................................................... 67
4.4.1 Afforestation and deforestation experiments ......................................... 67
4.4.2 Regrowth and forest conversion experiments ....................................... 72
4.4.3 Response times for all experimental types ............................................. 75
4.5 Results - Flow Duration Curves .................................................................. 76
4.6 Discussion ..................................................................................................... 84
4.6.1 Timing of streamflow response ............................................................... 84
4.6.2 Flow duration curves ............................................................................. 86
4.7 Conclusions .................................................................................. 87
CHAPTER 5 Parameterisation of the flow duration curve .......... 89
  5.1 Introduction ........................................................................... 89
  5.2 Methodology and data.............................................................. 90
    5.2.1 Model Description .............................................................. 90
    5.2.2 Data ................................................................................ 93
    5.2.3 Change in model parameters as a result of land use change .. 93
  5.3 Results .................................................................................... 95
    5.3.1 Model Performance ............................................................ 95
    5.3.2 Impact of vegetation change on model parameters .......... 97
  5.4 Discussion .............................................................................100
  5.5 Conclusions ...........................................................................102
CHAPTER 6 Adjusting flow duration curves for changes in forest cover ... 103
  6.1 Introduction ...........................................................................103
  6.2 Data .......................................................................................104
  6.3 Methodology ................................................................. 105
    6.3.1 Step 1: Estimating change in mean annual streamflow .... 109
    6.3.2 Step 2: Parameters of annual flow duration curves ......... 110
    6.3.3 Step 3: Cease-to-flow percentile or 95th percentile flow .. 111
    6.3.4 Adjusting the 95th or Cease to Flow percentile ............... 112
    6.3.5 Step 4: Conditional Median (initial estimate) ................. 120
    6.3.6 Step 5: Lower exponent (initial estimate) ......................... 121
    6.3.7 Step 6: Achieving mass balance ........................................ 122
  6.4 Results ...................................................................................123
    6.4.1 Observed flow during equilibrium period ....................... 126
    6.4.2 Mean annual yield predicted using the Zhang curves ....... 130
  6.5 Discussion .............................................................................134
  6.6 Conclusions ...........................................................................137
CHAPTER 7 Predicting the impact of forest cover change on water users at local and regional scales .......................................... 139
  7.1 Introduction ...........................................................................139
  7.2 Catchment description ...........................................................141
  7.3 Methods and Data .................................................................144
    7.3.1 Forest cover change scenarios and mean annual streamflow 144
    7.3.2 Determining suitable areas for plantation expansion ........ 144
    7.3.3 Determining changes in mean annual streamflow ......... 146
    7.3.4 Determining scenario areas .............................................. 148
    7.3.5 Adjusting FDCs and daily time series ............................... 149
    7.3.6 Linking to river systems models ....................................... 150
  7.4 Results ...................................................................................151
    7.4.1 Local catchments .............................................................. 151
    7.4.2 Impacts on downstream water users ............................... 155
  7.5 Discussion .............................................................................158
  7.6 Conclusions ...........................................................................161
CHAPTER 8 Summary and Conclusions ........................................... 163
  8.1 Introduction ...........................................................................163
  8.2 Summary ..............................................................................163
  8.3 Limitations and Future Research Needs .................................. 167
    8.3.1 Distribution of vegetation change across a catchment ...... 167
    8.3.2 Forest age impact on streamflow .................................. 169

viii
8.3.3 Linking the FDC to the flow time series ............................................. 171
8.4 Conclusions ......................................................................................... 172
References ................................................................................................. 175
Appendix A: Details of additional catchments used in Literature Review ...... 191
Appendix B - Results of adjusting flow duration curves for changes in
forest cover – All catchments ................................................................. 199
Pine Creek ............................................................................................... 199
Red Hill ................................................................................................. 200
Don 201
Lemon ...................................................................................................... 202
Wight ....................................................................................................... 203
Glendhu ................................................................................................... 204
Bosboukloof .......................................................................................... 205
Biesievlei ................................................................................................. 206
Cathedral Peak II .................................................................................. 207
Cathedral Peak III .................................................................................. 208
Lambrechtbsos A .................................................................................. 209
Lambrechtbsos B .................................................................................. 210
Tierkloof ................................................................................................. 211
Mokobulaan A ....................................................................................... 212
Mokobulaan B ....................................................................................... 213
Westfalia ................................................................................................. 214
Witklip ..................................................................................................... 215
Table of Figures

Figure 1–1: Time series and flow duration curve for a) ephemeral stream (dry 55% of the time), and b) perennial stream. From left to right, the 3 charts are: 1) time series, 2) time series plotted using log-scale, 3) FDC curve plotted on log-scale for the same period.......................... 4

Figure 1–2: Typical flow duration curves for perennial and ephemeral streams. .................................................................................................................. 5

Figure 2–1: Water yield changes as a result of changes in vegetation cover from Bosch and Hewlett (1982), Sahin and Hall (1996) and Stednick (1996). Results from Bosch and Hewlett and Stednick represent the maximum increase in the first 5 years after treatment for deforestation, regrowth and forest conversion experiments or maximum change in water yield for afforestation experiments. The results from Salin and Hall are the average increases in water yield in the first 5 years after treatment.............. 17

Figure 2–2: Distribution of water yield changes (scaled to 100% change in cover) a function of mean annual rainfall for the studies shown in ............ 17

Figure 2–3: Relationship between land cover, mean annual rainfall and mean annual evapotranspiration (from Zhang et al., 2001). .................. 19

Figure 2–4: Prediction of change in water yield based on the Zhang model compared with results from paired catchment studies for different vegetation types. .............................................................. 20

Figure 2–5: Change in annual water yield for four paired catchment studies in the USA. M4 – 100% Basal area cut. F7, upper half clear-cut (year 0), herbicides on upper half (2-7), lower half cut (year 4), herbicide on entire catchment (5-7). LR2 – Lower 24% clear-cut (year 0), mid slope 27% clear-cut (years 4-5), herbicide on lower and mid slope (Year 7) 40% Upper slope clear-cut (year 8-9), herbicide all catchment (Year 10). HB2 – 100% clear felled (Year 0), herbicide on entire catchment (Years 2-4). After Hornbeck et al., (1993). ................................................................. 23

Figure 2–6: Water yield increase for paired catchments, south Western Australia. Wights catchment (Ruprecht and Schofield, 1989), Yarragil (Stoneman, 1993), March Road (Bari et al., 1996), Lemons (Ruprecht and Schofield, 1991a). ................................................................. 24

Figure 2–7: Generalised curves from estimating the percentage reduction in total and low flow after 100% afforestation with pine and eucalypt afforestation (after, Scott and Smith, 1997). ........................................... 26

Figure 2–8: Changes in water yield as a percentage of rainfall for a deforestation experiment (Wights catchment) and an afforestation experiment (Biesievle catchment). Wights catchment is located in Western Australia with mean annual rainfall of 1200mm after Ruprecht and Schofield, 1989. Biesievle catchment is located in South Africa with mean annual rainfall of 1298mm, after Scott et al., 2000. ........................................... 27

Figure 2–9: Average monthly reductions in streamflow from the Glendhu catchment (afforestation with pines 1980) and Cathedral Peak II, South Africa (afforestation 1950-1955), Glenmorgan research Farm, India.
Value 1 – 12 on the x-axis represent the months January to December for
Southern Hemisphere catchments and July to June in the Northern
Hemisphere catchment. ............................................................. 30

Figure 2–10: Flow Duration curves for the Red Hill catchment, near
Tumut, New South Wales, Australia. 1 year old pines and 8 year old pines
(after Vertessy, 2000). ............................................................ 33

Figure 2–11: Flow Duration curves for the Wights catchment in south
Western Australia. (Based on a water year from April to March). .............. 34

Figure 2–12: Flow duration curve from the Glendhu experimental
catchments New Zealand. 1980 – during the calibration period (both
1999 – 16 years after pine plantation established. (McLean, 2001). ....... 35

Figure 2–13: Flow duration curves for the first year after the clear-felling
treatment – Hubbard Brook experimental forest (after Hornbeck et al.,
1997). ....................................................................................... 36

Figure 3–1: Location of experimental catchment studies ......................... 44

Figure 4–1: Fit of the sigmoidal model to changes in streamflow scaled to
100% of the catchment area treated (Red Hill, Australia). The y axis
shows the change in streamflow from the predicted streamflow in the
catchment if no change in forest cover had occurred. .................................. 68

Figure 4–2: Fit of the sigmoidal model to the percentage changes in
streamflow scaled to 100% of the catchment area treated (Red Hill,
Australia). ....................................................................................... 68

Figure 4–3: Percentage change in streamflow for afforestation
experiments....................................................................................... 69

Figure 4–4: Time taken for change in streamflow to occur in afforestation
catchments. The change is divided into three sections. The time taken
for the initial 10% change, the time for the middle 80% change, and the
time taken for the final 10% of the total change. Letter indicates the forest
type, E indicates planted with Eucalypt species and P indicates planted
with either *Pinus radita* or *Pinus patula* ........................................ 70

Figure 4–5: Response of all deforestation experiments to age of
vegetation, with sigmoidal curve fitted....................................................................... 71

Figure 4–6: Time taken for the change in streamflow to occur in
deforestation experiments. The response time has been divided into three
sections, the time for the initial 10% of the change to occur, the time for
the middle 80% of the change, and the time for the final 10% change .......... 72

Figure 4–7: Typical response curve for regrowth experiments with
coefficient of efficiency of 0.77 (Stringybark Creek). ..................................... 73

Figure 4–8: Typical response curve for regrowth experiments with
coefficient of efficiency of 0.40 (Ettercon 1). ............................................... 73

Figure 4–9: Response of regrowth and forest conversion experiments to
age of vegetation, results scaled to 100% of catchment treated. Only for
catchments with coefficient of efficiency greater than 0.5 for the fitted curve are shown. ................................................................. 75

Figure 4–10: Timing of streamflow changes for different types of treatment. ................................................................. 76

Figure 4–11: Flow duration curves for the rapid response catchments. Plots on the left (A and B) show the first year of the calibration period, plots on the right (C and D) show the FDC following land use change. The flows in the lower figures (B and D) are plotted on a log scale. The predicted FDCs show the FDCs that would be expected if no change in land use had occurred. It should be noted at on Figure D the observed FDCs for Mokobulaan A and Westfalia D do not appear, as there was no flow in these catchments during the year plotted........................................... 78

Figure 4–12: Flow duration curves for the medium response catchments. Plots on the left (A and B) show the first year of the calibration period, plots on the right (C and D) show the FDC following land use change. The flows in the lower figures (B and D) are plotted on a log scale. The predicted FDCs show the FDCs that would be expected if no change in land use had occurred................................................... 79

Figure 4–13: Flow duration curves for the slow response catchments. Plots on the left (A and B) show the first year of the calibration period, plots on the right (C and D) show the FDC following land use change. The flows in the lower figures (B and D) are plotted on a log scale. The predicted FDCs show the FDCs that would be expected if no change in land use had occurred................................................... 80

Figure 4–14: Flow duration curves for remaining afforestation catchments. Plots on the left (A and B) show the first year of the calibration period, plots on the right (C and D) show the FDC following land use change. The flows in the lower figures (B and D) are plotted on a log scale. The predicted FDCs show the FDCs that would be expected if no change in land use had occurred................................................... 81

Figure 4–15: Percentage reduction in streamflow for different percentile flows for the afforestation experiments................................................. 82

Figure 4–16: Reduction in streamflow by volume for different percentile flows for the afforestation experiments................................................. 82

Figure 4–17: Flow duration curves for the deforestation experiments. Plots on the left show the first year of the calibration period, plots on the right show the FDC following land use change. The flows in the lower figures (B and D) are plotted on a log scale. The predicted FDCs show the FDCs that would be expected if no change in land use had occurred.............. 83

Figure 5–1: 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. ................................................. 92

Figure 5–2: 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................................................. 95
Figure 5–3: Volume comparison for all years for all catchments (total of 1838 FDC). Showing the percentage of catchments where the predicted volume is within 1%, 5% and 10% of actual volume................................................................. 96

Figure 5–4: Spread in residuals for selected model percentiles for the Jonkershoek experimental group. ................................................................. 97

Figure 5–5: Comparison of fitted parameters (s, c_u, c_l) values for the afforestation control catchments. The thick line represents the median, the box the 25th and 75th percentile and the whiskers the range of the parameters for the annual FDCs in each control catchment........................................ 98

Figure 5–6: Correlation between fitted annual FDC parameters for all afforestation experimental catchments (both treated and control catchments). Figure 5-6A shows the relationship between the slope and upper exponent, Figure 5-6B shows the correlation between the slope and lower exponent, Figure 5-6C shows the correlation between the upper and lower exponents. .................................................................................. 99

Figure 6–1: Linking the Zhang curves to the FDC. Using the Zhang Curves (a), the change in mean annual streamflow can be predicted (\(\Delta\) Streamflow). This is linked to the FDC (b) as the shaded area between the FDC for Grass and FDC for forest is equal to \(\Delta\) Streamflow .................... 106

Figure 6–2: Normalising the FDC to achieve common parameter space ...... 107

Figure 6–3: Flow chart showing the key steps in adjusting the FDC for land use change...................................................................................... 108

Figure 6–4: Relationship between mean annual rainfall and mean annual runoff for grass and forested catchments, adopted from Zhang et al. (2001). .................................................................................................................. 109

Figure 6–5: Simple bucket model used to model the percentage of time flow occurs. Here, P is precipitation, I is interception, ET is the Evapotranspiration, Q_{direct} is the direct runoff, Q_{base} is the baseflow, S_{base} is the reference point of the model and is set to a value of 0, S_{max} and S_{ET} are the parameters of simple bucket model......................................................... 113

Figure 6–6: ET function proposed by Farmer et al., 2003 and adopted in the simple bucket model ..................................................................... 114

Figure 6–7: Examples of surface flow, interflow and baseflow in hydrograph recessions ............................................................................. 117

Figure 6–8: Examples of different flow components in recessions .......... 117

Figure 6–9: Procedure for determining the change from interflow to baseflow for a recession 28 days in length. A, shows Line 1 fitted through the first 2 points and Line 2 fitted through the last 27 points. B, shows Line 1 fitted through the first 3 points and Line 2 fitted through the remaining 26 points. C, shows the two lines that have the maximum weighted \(R^2\) or change factor (9 points in Line 1 and 20 points in Line 2). D shows the Line 1 fitted through the entire recession................................. 119

Figure 6–10: Typical relationship between the conditional mean and conditional median streamflow for Bosboukloof catchment............... 121
Figure 6–11: Zhang curves for 100% grass and 100% forest with observed change in streamflow shown for a subset of the experimental catchments. Only catchments with between 70 - 100% change in forest cover and a less then 20% difference between the rainfall during the calibration and equilibrium period have been shown.

Figure 6–12: Spread in the recession constant (k) for each catchment showing the spread in the k values for the calibration and new equilibrium periods. The thick line represents the median, the box the 25th and 75th percentile and the whiskers the range of the recession constants for the individual recessions for each catchment. The red line shows the mean value of the recession constant.

Figure 6–13: Third worst fit (coefficient of efficiency of 0.51) of the predicted FDC for the observed flows during the equilibrium period, shown in both linear and log space (Lambrechtsbos B).

Figure 6–14: Third best fit of the predicted FDC (coefficient of efficiency of 0.97) for the observed flows during the equilibrium period, shown in both linear and log space (Glendhu).

Figure 6–15: Third worst fit of the predicted FDC for the predicted mean annual flow.

Figure 6–16: Third best fit of the predicted FDC for the predicted mean annual flow.

Figure 6–17: Comparison between observed and predicted flows for the 5th, 50th, and 95th percentiles. E values represent the coefficient of efficiency or the comparison to the 1 to 1 line, the closer the value of E to 1 the better the prediction.

Figure 6–18: Comparison between coefficient of efficiencies (E) for the FDC Parameterisation, the predicted FDC using the observed change in mean annual flow (MAF), predicted FDC using the predicted MAF.

Figure 7–1: Location of Murrumbidgee catchment (a) shows the location of the main towns and irrigation areas, and, (b) shows sub-catchments considered in the Murray uplands project.

Figure 7–2: Steps in linking land use and river planning models to assess impacts on water resources and environmental flows.

Figure 7–3: Areas considered suitable in each of the decision layers. (a) rainfall greater than 500mm, (b) current vegetation, (c) reserves, (d) productivity greater than 18 m3/ha/y, (e) area within 80 km of wood processing mills and (f) woody vegetation less than 84% of area.

Figure 7–4: Combining suitable area, rainfall and water balance model (Zhang et al. 2001) to determine areas that have the highest and lowest impact on water resources. (a) suitable area, (b) rainfall grid, (c) mean annual water balance model showing data used to develop the relationships, (d) suitable areas showing predicted reduction in water yield for each grid cell.

Figure 7–5: Areas for plantation expansion considered in each scenario. The black areas indicate HWYR, while dark grey areas show the LWYR.
Figure 7–6: Predicted change in Adelong creek FDC. The insert looking at the low flow section of the curve, show the four flow classes for the Adelong Creek water sources based on the Batlow Road gauge. Very low flows (< 12 ML/day), Class A refers to low flows (flows between 12 and 20 ML/day), Class B (medium flows - 20 and 30 ML/day), Class C (high flows > 30ML/day).

Figure 7–7: Box plot showing the spread in the change in allocations. Solid line shows the median, thin lines show the 25th and 75th percentiles and the whiskers show the spread. 30,000ha high and 30,000ha low indicate the HWYR and LWYR scenarios respectively.

Figure 7–8: Spread in annual reductions in streamflow. 30,000ha high and 30,000ha low indicate the HWYR and LWYR scenarios respectively, changes in flow are shown for Wagga Wagga and Balranald.

Figure 7–9: Spread in annual reduction in diversions. Changes in total diversions refer to diversions to MIA, CIA, and inter-valley transfers. Changes in diversions to Lowbidgee refer to Lowbidgee flood control and irrigation district as shown of Figure 7-1a.

Figure 8–1: Affects of different rotation lengths and periods of uptake (or change) on age distribution in areas converted from 100% grass/agriculture to 100% forest. (From Brown et al. 2006a)

Figure 8–2: Impact of different rotation lengths and periods of uptake on predicted streamflow. (From Brown et al. 2006a)
Table of Tables

Table 2-1: Seasonal responses in water yield.................................................29

Table 2-2: Summary of results from paired catchment studies, highlighting
the limitation and uses of the transient vegetation studies (regrowth and
forest conversion experiments) and permanent vegetation studies
(afforestation and deforestation experiments) for making generalisation at
different timescales and list references for predictive tools currently
available ...........................................................................................................41

Table 3-1: Description of Black Spur Experimental Catchments ..................46

Table 3-2: Description of Ettercon Experimental catchments ......................46

Table 3-3: Description of Monda Experimental catchments .......................47

Table 3-4: Description of Myrtle Experimental catchments .......................47

Table 3-5: Description of Coranderrk Experimental catchments .................48

Table 3-6: Description of the Tantawangalo Creek catchments .................48

Table 3-7: Description of Yambula state forest experimental catchments
(Roberts, 2001) ..............................................................................................49

Table 3-8: Description of the HJ Andrews experimental catchments ..........49

Table 3-9: Description of the Coyote Creek experimental catchments ........50

Table 3-10: Description of the Fox Creek experimental catchments ..........51

Table 3-11: Description of the Stewarts Creek catchment experiment .........52

Table 3-12: Description of the Collie River Basin experimental catchments ...53

Table 3-13: Description of the Witklip experimental catchments ...............53

Table 3-14: Description of the Red Hill catchment experiment ..................54

Table 3-15: Description of the Glendhu catchment experiment .................55

Table 3-16: Description of the Cathedral Peak research catchments ..........55

Table 3-17: Description of the Jonkershoek experimental catchments .........56

Table 3-18: Description of the Mokobulaan experimental catchments .........57

Table 3-19: Description of the Westfalia experimental catchments ..........58

Table 3-20: Description of the Plynlimon experimental catchments ..........58

Table 4-1: Coefficient of efficiency (E) for each sigmoidal curve for all
afforestation experiments, indicating that for the majority of catchments
the percentage change in streamflow conform to the shape of sigmoidal
model better than the absolute change in streamflow ..................................69

Table 4-2: Coefficient of efficiency for each sigmoidal curve for all
deforestation experiments .............................................................................71

Table 4-3: Coefficient of efficiency (E) for all regrowth and forest
conversion experiments ...............................................................................74
Table 4-4: Regression parameters and $R^2$ from Equation 4-5 for each afforestation and deforestation study. .................................................................77

Table 5-1: Summary of experimental catchment groups (Details and key references can be found in Best et al., 2003a). ..............................................94

Table 5-2: Period of record used to test for trends in change in water yield.....94

Table 5-3: Average coefficient of efficiency for each catchment group. ........97

Table 5-4: 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. ........................................98

Table 6-1: Comparison between the observed changes in streamflow and changes predicted from the Zhang curves .............................................124

Table 6-2: Results from FDC adjustment methodology using observed flow during equilibrium period ...............................................................127

Table 6-3: Results from FDC adjustment methodology using predicted change from Zhang curves .................................................................130

Table 7-1: Gauging stations used to provide inflows to the Murrumbidgee IQQM modelling .................................................................142

Table 7-2: Changes in forest cover and streamflow in upland sub-catchments of the.................................................................152

Table 7-3: Changes in percentile flows in tributary catchments (30,000ha HWYR scenario) and cease to flow (CTF) percentile under current and HWYR scenario .................................................................154

Table 7-4: Changes in percentile flow in tributary catchments (30,000ha LWYR scenario) and change in cease to flow (CTF) percentile. Note: Blanks indicate that there was no flow under baseline conditions ..........154

Table 7-5: Mean annual reductions in allocations, diversions and streamflow.................................................................155
CHAPTER 1  Introduction

Extensive land use changes within Australia since European settlement have caused a change in the hydrologic regime of many catchments. The Forest Plantations 2020 (DPIE, 1997) vision is one of a number of initiatives that aim to increase the area of forestry within Australia. Therefore, an increase in forest area needs to be considered as a likely major land use change in Australia. The 2020 vision, for example, states that by the year 2020 the area of tree plantation within Australia will treble. If implemented, this will influence streamflow at both the local and regional scale. The response of catchments to such land use change is likely to vary in both space and time. These variations are currently poorly quantified, but it is expected that they will be significant and need to be considered by natural resource managers. In order to develop sustainable land management options it is necessary to develop tools that quantify both the positive and negative impacts of these proposed land use changes.

One of the potential negatives of increasing forest cover is a reduction in streamflow and tools are required that predict the effect of forest cover changes on streamflow. Models are available that allow the changes in mean annual water yield associated with afforestation to be predicted. However, it is perhaps even more important to predict the effects of afforestation on the temporal variability of streamflow. This is because models for water allocation, water quality management, and environmental flow management all require an ability to predict how monthly or daily flow statistics will be affected by changing land use. For example, in Australia water allocation models such as the Integrated Quantity and Quality Model (IQQM) (Simons et al., 1996) and Resource Allocation Model (REALM) (Diment, 1991) use daily or monthly data to assess the impact of policy options on water consumers.

Forest cover changes are likely to impact on a number of aspects of the flow regime including seasonality and variability. Unfortunately, our understanding of the seasonal impact of forest cover change on streamflow is limited and there have been no effective tools available for predicting changes at these shorter time scales. It is generally understood that forest cover affects not only rainfall interception, which directly influences surface runoff, but also deep drainage (Zhang et al., 1999). This impact on deep drainage, which occurs via changes in evapotranspiration, affects the baseflow in a catchment. However, it is difficult to quantify these changes where no detailed experimental data are available. The degree of control on these processes by vegetation depends upon the climate, soil, and other catchment characteristics. One of the difficulties in predicting changes in streamflow at the monthly or daily time step is to
Chapter 1: Introduction

decide on a method that can capture the characteristics of the streamflow time series in the simplest way possible. A commonly used approach for making such predictions is to rely on detailed physically based models or statistical models derived from paired-catchment studies (Vertessy et al., 1993; Scott and Smith, 1997). These methods are either problematic to apply due to the extensive data requirements or constrained by local data, so an alternative approach is required, the development of which is the focus of this thesis.

One way to evaluate the effect of afforestation on streamflow at shorter timescales is to examine the change in a catchment’s flow duration curve (FDC) following a change in forest cover. A FDC represents the relationship between the magnitude and frequency of streamflow for a catchment and provides an estimate of the percentage of time a given flow is equalled or exceeded. FDCs are commonly used in hydrology. The adoption of the FDC as a method to summarise the key features of a time series of streamflow allows easy identification of differences in the statistical distribution between two streamflow time series. FDCs also have direct application in hydrology for hydropower, water allocation, and water quality management. Most studies involving FDC analysis aim to provide information on the relationships between flow and the frequency at which that flow occurs for catchments under a static land-use and stationary climate (Fennessey and Vogel, 1990), whereas in this thesis a method is developed for predicting the impact that changing forest cover has on a catchment’s FDC. There are several aspects of sub-year response that could be considered in this thesis, including seasonality and monthly flow variability. However, to keep the scope this thesis tractable, it concentrates on the use of FDCs constructed using daily flow data at the annual and mean annual time step.

1.1 Thesis aims and objectives

This thesis aims to develop a procedure for predicting responses in a catchment’s FDC following a change in forest cover. This requires the identification of appropriate models that can be manipulated to reflect observed responses that is sufficiently simple for practical use.

This aim is achieved by addressing the following tasks and objectives:

1. review the available literature on paired catchment studies to establish what predictive models are currently available at different time scales (Chapter 2);
2. undertake a consistent analysis of worldwide paired catchment data (summarised in Chapter 3) to assess the impact of different types of treatment on streamflow at different temporal scales (Chapter 4);

3. describe the FDC through a set of parameters that can be used to model many FDCs (Chapter 5);

4. develop and test a method to adjust the parameter values of the FDC parameterisation for a change in forest cover (Chapter 6); and,

5. apply the method to a large river basin to investigate the impacts on water availability at both a local and regional scales (Chapter 7).

The remainder of this chapter outlines some of the key concepts used within this thesis and then gives a brief description of the contents of each chapter.

1.2 Paired catchment studies

Paired catchment studies have been widely used to assess the likely impact of land use change on streamflow around the world. Such studies involve the use of two catchments with purportedly similar characteristics in terms of slope, aspect, soil, geology, area, precipitation, and vegetation located near each other. Following a calibration period, where both catchments are monitored, one of the catchments is then subject to treatment (changed land cover characteristics) and the other remains as a control. Using the control catchment to determine the flow that would have occurred in the treated catchment, with no forest cover change, the impact of the treatment on streamflow can be determined by comparing this with the observed flow in the treated catchment. This approach allows for the removal of climatic variability, and changes in streamflow can be attributed to changes in vegetation. Paired catchment studies reported in the literature can be divided into four broad categories: afforestation experiments, regrowth experiments, deforestation experiments, and forest conversion experiments. This thesis uses data from paired catchment studies around the world to assess the impact of changes in forest cover on streamflow at different temporal scales and to develop a predictive model that can be used to aid the appropriate planning of forest cover change.

1.3 Flow Duration Curves

A FDC is a simple and powerful tool that characterises the statistical distribution of flow at the outlet of a catchment. Its shape is determined by the size and the physiographic
characteristics of the catchment and the associated climate. The shape of the flow duration curve is also influenced by water resources development and land use type (Smakhtin, 1999). The FDC is widely used in hydrology as it provides an easy way to display the complete range of flow. It is adopted in this thesis as the change in a catchment’s FDC provides a useful measure of how the distribution of streamflow may alter following a change in forest cover. A FDC can be constructed from daily streamflow data by ranking the flow from the maximum to the minimum, and determining the percentage of time each flow value is exceeded. Figure 1–1 provides two examples of the construction of the FDCs and the corresponding daily time series data. Figure 1–1a shows an ephemeral stream, while Figure 1–1b shows a perennial stream.

![Figure 1–1: Time series and flow duration curve for a) ephemeral stream (dry 55% of the time), and b) perennial stream. From left to right, the 3 charts are: 1) time series, 2) time series plotted using log-scale, 3) FDC curve plotted on log-scale for the same period.](image)

The FDC for a given catchment represents several key characteristics of the streamflow time series. For example, in Figure 1–2, the high-variability perennial stream will only exceed a flow of 0.1 mm/day (averaged over the catchment) for about 50% of the time. For the ephemeral stream, there is no flow for about 57% of the time. By displaying flows in this fashion, a better appreciation of the complete range of streamflow and its variability can be observed. The general slope of the curve represents streamflow variability, while the absence or existence of an x-intercept indicates the perennial or ephemeral nature of the stream. For regulated catchments,
flow duration curves tend to be relatively flat indicating more constant flow, while for catchments with highly variable rainfall and little water storage capacity, the slopes of flow duration curves will be very steep.

![Figure 1–2: Typical flow duration curves for perennial and ephemeral streams.](image)

A FDC can be depicted for different time intervals, such as months or days. It can be based on all the flows in a given year (annual flow duration curve) or for a subset of annual flows (seasonal flow duration curve). In this thesis, the focus is on the FDC constructed from daily flow data for the annual and mean annual time step.

### 1.4 Modelling approach

The procedure outlined in this thesis to adjust the FDC for changes in forest cover uses a downward or “top-down” approach to model development (Sivapalan et al., 2003). This approach differs from the physically based modelling approach in that it tries to capture the overall response of a catchment based on the analysis and interpretation of the observed response data (i.e. the streamflow data at the catchment outlet). The level of process understanding included in the model is based on the behaviour of the observed response data, rather than the notion that a particular process must be included in the modelling. This means that while a model developed using a “top-down” approach may have good predictive capability for the overall streamflow, it cannot be used to assess the effect forest cover may have on the components of streamflow. For example, if the research question were to determine the relative impact changing forest cover has on rainfall interception and deep-drainage, a more
process-based model or observations of these processes would be required. However, as the aim of this thesis is to develop a model that predicts the overall response in the FDC, the “top-down” modelling approach provides an appropriate means for developing a model that has predictive capability while relying on readily available data.

The mean annual water balance model of Zhang et al. (1999) and Zhang et al. (2001) is a good example of the downward modelling approach. This model allows the effect of forest cover changes on mean annual streamflow to be predicted using readily available data and provides a practical tool known as the “Zhang curves” for predicting the long-term consequences of afforestation or deforestation on mean annual evapotranspiration at the catchment scale. The Zhang model is based on a worldwide data set from over 250 catchment studies and has an advantage over traditional process-based models in that the required input data (mean annual rainfall and percentage forest cover) are readily available at both the catchment and regional scale.

1.5 Thesis Outline

The research in this thesis is presented in eight chapters:

Chapter 1 outlines the aims and objectives of the research undertaken and the relevance to proposed major land use changes in Australia.

Chapter 2 provides a literature review of paired catchment studies. This review summarises the current state of understanding of the impact of vegetation changes at different temporal scales. It provides a number of examples of the observed response times associated with changes in forest cover and the changes in FDCs following permanent changes in forest cover over significant portions of the catchment. This review has been published as a journal article in the Journal of Hydrology. A summary of the knowledge gaps addressed in this thesis is provided at the end of this chapter.

Chapter 3 provides a description of the data used in the thesis.

Chapter 4 describes a consistent analysis of paired catchment data collated as part of this thesis, with the aim of trying to draw some more general conclusions about the time delays associated with changes in forest cover, the different seasonal responses and the responses in flow duration curves.

Chapter 5 builds on the analysis of data in chapter 4 and develops a method to parameterise the FDC. Paired catchment data are used to gain an understanding of
how vegetation changes impact on each of the parameters of the FDC. The work was published as a peer reviewed conference paper for MODSIM 2003.

Chapter 6 develops a methodology to adjust the parameters of the FDC model developed in Chapter 5. This FDC adjustment methodology is used to predict responses in the FDCs of the afforestation and deforestation paired catchment studies described in Chapter 3.

Chapter 7 applies the methodology developed in Chapter 6 to catchments in the Upper Murrumbidgee River Basin for two possible forest-cover change scenarios. The adjusted FDC is then used to modify the streamflow time series to allow downstream impacts on water users within to be investigated. This research has been published in Forest Ecology and Management.

Chapter 8 provides a summary for the thesis and outlines the conclusions that have been drawn during this research. Further research needs are also identified.
CHAPTER 2  Literature Review

With the exception of the concluding paragraph, outlining the research questions addressed in this thesis, the chapter has been published in its entirety in the Journal of Hydrology, Volume 310, Issue: 1-4, pages 28 to 61.

2.1 Introduction

Paired catchment studies have been widely used as a means of determining the magnitude of water yield changes resulting from changes in vegetation. A number of review articles have summarised the results of these studies. Bosch and Hewlett (1982) reviewed catchment experiments to determine the effect of vegetation change on water yield. Two types of experiments were reviewed, paired catchment studies and time-trend studies that provide circumstantial evidence of the influence of catchment management on water yield. Since 1982, a number of additional paired catchment studies have been reported in the literature. The results of some of these studies have been summarised in the subsequent reviews of Hornbeck et al. (1993), Stednick (1996) and Sahin and Hall (1996). Vertessy (1999, 2000) reviewed the available literature on paired catchment studies with respect to forestry and streamflow. These two reviews provide a comprehensive summary of the present understanding of the impact of vegetation change on water yield, with particular reference to Australian conditions.

This paper focuses on the impact of vegetation changes on water yield at different temporal scales. Firstly, at the mean annual time scale results from previous paired catchment reviews are compared to a mean annual water balance model of Zhang et al. (2001), known as the “Zhang curves”. The Zhang curves were derived from both paired catchment and time-trend studies and were developed to predict the impacts of permanent vegetation changes on evapotranspiration and water yield at the catchment scale. The adjustment time or time to reach a new equilibrium is then assessed for the different types of paired catchment experiments. This helps in understanding how responses between permanent and transient vegetation changes differ. A summary of papers presenting seasonal changes in water yield is then provided in terms of responses observed in different climatic zones. However, it is important to note that the magnitude of mean annual change, the adjustment time and seasonal response do not tell the whole story in relation to the impact of vegetation change on water yield. For many water resource management issues it is necessary to have an understanding

* The co-authors of this paper were my supervisors and provided guidance in the research
of how vegetation will influence the distribution of daily flows or the flow duration curve (FDC). This paper uses the FDC as a means of displaying how alterations to a catchment’s vegetation can affect the distribution of flows. The effects of vegetation changes on the FDC are presented at both mean annual and seasonal temporal scales. This review includes 72 paired catchment studies in addition to those reviewed by Bosch and Hewlett (1982) bringing the total number of paired catchment experiments reviewed to 166. Details of the additional 72-paired catchments can be found in Appendix A.

2.2 Paired catchment studies

Paired catchment studies involve the use of two catchments with similar characteristics in terms of slope, aspect, soils, area, climate and vegetation located adjacent or in close proximity to each other. Following a calibration period, where both catchments are monitored, one of the catchments is subjected to treatment and the other remains as a control. This allows the climatic variability to be accounted for in the analysis. The changes in water yield can then be attributed to changes in vegetation. The paired catchment studies reported in the literature can be divided into four broad categories:

1. Afforestation experiments – conversion of shorter vegetation (e.g. pasture) to forest. Examples can be found in South Africa (Scott et al., 2000), New Zealand (McLean, 2001), Australia (Hickel, 2001) and the United Kingdom (Kirby et al., 1991; Johnson, 1991)

2. Regrowth experiments – these look at the effects of forest harvesting where regrowth is permitted. Experiments in this category constitute the majority of the paired catchment studies worldwide. They involve the removal of vegetation from a percentage of a catchment followed by regrowth of the same vegetation type (Stednick, 1996).

3. Deforestation experiments – the conversion of densely vegetated land to grass or pasture. The Collie catchments in Western Australia (Ruprecht and Schofield, 1989; Ruprecht and Schofield, 1991a.b; Ruprecht et al., 1991; Schofield, 1991) are an example.

4. Forest conversion experiments – the replacement of one forest type with another. This includes the conversion from softwood to hardwood, deciduous to evergreen or pine to eucalypt. The Stewarts Creek experiment provides an
example of the conversion of native vegetation to pine in Victoria, Australia (Mein et al., 1988; Nandakumar, 1993).

The paired catchment experiments reviewed by Bosch and Hewlett (1982), Whitehead and Robinson (1993), Sahin and Hall (1996) and Stednick (1996) focused mainly on regrowth experiments, where harvesting of forests is undertaken followed by the regrowth of the same vegetation type. While the activities involved in regrowth of vegetation may affect the short-term water yield, permanent vegetation changes such as afforestation and deforestation are likely to have a much greater long-term impact on streamflow and the associated issues, such as salinity and water resource security.

Vertessy (1999) highlighted some of the problems with using regrowth experiments for estimating water yield increases as a result of permanent vegetation change. Where forests are permitted to regenerate, only data obtained in the first few years following treatment are used to build the relationships between percentage change in cover and change in water yield. This is because data in subsequent years are affected by regrowth and are not representative of the water yield under a new vegetation type. Three problems were highlighted in relation to the use of such data:

1. it takes time for a catchment to adjust its runoff behaviour following vegetation change;

2. soil compaction and disturbance during logging and regeneration burning can temporarily increase overland flow and change the pattern of streamflow; and

3. due to the short data set used to build the linear relationships predicting water yield change, natural variability in the water yield due to climatic variability may have a strong influence on the results.

Various methods have been applied in the analysis of paired catchment data to assess the impacts of vegetation changes on water yield at various time scales. The most common method is to produce a linear regression between the annual discharges from the control and treated catchments during the calibration period (Hornbeck et al., 1993). The regression equation is then used to predict the water yield that would have occurred in the treated catchment if the treatment had not taken place. The difference in the observed and the predicted streamflow is then assumed to be due to vegetation change as this method provides a control over climatic variability (Bari et al., 1996). Although this approach is most commonly used with annual data, it has also been used
with monthly data and the quick flow and baseflow components of streamflow (Bari et al., 1996).

South Africa has a very comprehensive set of paired catchment studies that have been used to assess the impacts of afforestation on water yield. A significant amount of literature is available on these catchments and a number of different methods have been used to assess the impacts of afforestation on water yield at an annual scale. The latest South African work is summarised in Scott et al. (2000) and provides details of all the afforestation experiments undertaken in South Africa. To predict the impact of afforestation on annual streamflow and the change in water yield with time due to development of plantations, Scott and Smith (1997) developed an empirical model that predicts the percentage reduction in water yield with time.

Seasonal or monthly analysis of paired catchment data is less common than annual analysis. Typically, linear regression of monthly data during the calibration period (making no adjustments for the serial correlation) is used to establish pre-treatment relationships between the control and the treated catchments. Lane and Mackay (2001) adopted this method to analyse the Tantawangalo Creek catchments in New South Wales as insufficient annual data were available during the pre-treatment period to develop annual relationships. Scott and Lesch (1997) also used monthly data in their analysis of the Mokobulaan experimental catchments in South Africa. To adjust for the changes in soil water storage between months, Scott and Lesch (1997) used both streamflow and rainfall data as independent variables in a monthly multiple regression model. The rainfall term used was an antecedent wetness index incorporating the previous month’s wetness index and the rainfall in the present month. Their analysis considered annual flows as well as wet and dry season flows.

Watson et al. (2001) developed an improved method to assess the water yield changes from paired catchment studies and applied these to the Maroonhdah experimental catchments in Victoria, Australia. They argued that the short pre-treatment periods in most paired catchment studies limits the reliability of the annual regression analyses and instead recommended the use of monthly data with an explicit seasonal component. The advantage of using monthly data is that there are 12 times as many data points, than in the analysis of annual data. However, it is important to note that while the use of monthly data represents more information, if the monthly serial correlation is significant, it does not represent 12 times the information in the annual data.
Water yield changes from paired catchment studies have been reported in the literature at mean annual, annual and mean seasonal or mean monthly temporal scales. The following sections on mean annual water yield, response times, mean seasonal water yield, and flow duration curves summarise the use of paired catchments for assessing the impacts of vegetation changes on water yield and flow regime. Specific examples from Australia, South Africa and New Zealand are used to highlight some of the conclusions that can be drawn about permanent vegetation change from paired catchment studies.

2.3 Mean annual water yield

A number of reviews have been undertaken to draw generalisations from paired catchment studies, particularly in reference to the changes in water yield resulting from changes in forest cover. The first of these reviews was by Hibbert (1967). Thirty nine experimental catchments were reviewed and the following conclusions were drawn:

- reduction in forest cover increases water yield;

- establishment of forest cover on sparsely vegetated land decreases water yield; and

- the response to treatment is highly variable and, for the most part, unpredictable.

In 1982, Bosch and Hewlett undertook a further review of paired catchments. In order to include afforestation experiments in their analysis, they assumed that the maximum decrease in water yield was analogous to the maximum increase in water yield during the first 5 years after treatment for deforestation experiments. This allowed general conclusions to be drawn about the impact of forest cover on water yield. The use of maximum increase in water yield in the first 5 years after treatment may bias the results because the maximum increase is likely to be affected by climate variability and the assumption that adjustment in water yield occurs in less than 5 years from the time of treatment. In reviewing 94 experimental catchments, they concluded:

- reducing forest cover causes an increase in water yield;

- increasing forest cover causes a decrease in water yield;

- coniferous and eucalypt cover types cause ~40mm change in annual water yield per 10% change in forest cover;
deciduous hardwoods are associated with ~25mm change in annual water yield per 10% change in cover;

brush and grasslands are associated with a ~10mm change in annual water yield per 10% change in cover;

reductions in forest of less than 20% apparently cannot be detected by measuring streamflow; and

streamflow response to deforestation depends on both the mean annual precipitation of the catchment and on the precipitation for the year under treatment.

The reviews of Hibbert (1969) and Bosch and Hewlett (1982) mainly focused on catchments from temperate zones. Bruijnzeel (1988) looked at the impacts of vegetation changes on water yield, particularly dry season flows in the tropics. From this work, it was concluded that:

surface infiltration and evapotranspiration associated with the representative types of vegetation play a key role in determining what happens to the flow regime after forest conversion;

if infiltration opportunities after forest removal decrease to the extent that the amount of water leaving an area as quick flow exceeds the gain in baseflow associated with decreased evapotranspiration, then diminished dry season flows will result;

if surface infiltration characteristics are maintained the effect of reduced evapotranspiration after clearing will show up as an increase in baseflow; and

the effect of reforesting will not only reflect the balance between changes in infiltration and evapotranspiration, but will also depend on the available water storage capacity of the soil.

The conclusion that under deforestation either a decrease or an increase in baseflow may occur seems to conflict with many of the results of paired catchment studies in temperate zones, in which increases in baseflow are almost uniformly observed (Hornbeck et al., 1993). This increase in baseflow is also observed in the tropical catchments in Africa. Blackie and Edwards (1979) observed increases in baseflow in cultivated catchments compared to forested catchments. However, in these
catchments there were no long term changes in the infiltration rates. These results highlight that different process responses can cause similar changes in mean annual water yield. The water yield changes can be the result of changes in surface runoff, changes in baseflow or changes in both baseflow and surface runoff. The process changes resulting from alterations in vegetation have important seasonal implications. For example, in the Konta area, east Java, forest clearing for dry-land agriculture and urbanisation has resulted in decreased infiltration, which has increased surface runoff and reduced recharge. This has resulted in lower baseflow during the dry season and higher flow during the wet season (Bruijnzeel, 1988). In Mbeya, Tanzania, the difference in streamflow between a forested and cultivated catchment are primarily due to the differences in dry season transpiration, with little or no change in the surface runoff as infiltration rates have remained unchanged (Edwards, 1979). These seasonal responses are discussed further in Section 2.5.

Reviews by Stednick (1996) and Sahin and Hall (1996) expanded on the work by Bosch and Hewlett (1982). Stednick (1996) reviewed results of studies from the United States and looked only at annual water yield changes as a result of timber harvesting. The focus was on the effect of the percentage of area treated to detect changes in streamflow. Different hydrologic areas were defined based on temperature and precipitation regimes and it was concluded that:

- in general, changes in annual water yield from forest cover reductions of less than 20% of the catchment could not be detected by streamflow measurement; and

- regionalisation of data suggested this value might change depending on the temperature and precipitation of the area. For example, a measurable increase in streamflow is observed for treatments of 15% of the catchment area in the Rocky Mountains compared with the Central Plains over 50% of the catchment area needs to be treated before changes in water yield can be detected.

The conclusion that at least 20% of a catchment needs to be treated before detectable changes in water yield occur agrees with the conclusions of Bosch and Hewlett. However, while the changes in water yield for treatment areas of less than 20% are not be statistically detectable, at the larger catchment scale it is often important to be able to predict the changes in water yield when less then 20% of the catchment is treated. This difference between being able to make predictions and being able to detect the changes is important to consider when using results for predictions.
Sahin and Hall (1996) used a similar approach to Bosch and Hewlett (1982) in their analysis of 145 experimental catchments in dividing the vegetation types into broad categories (hardwood, conifer, conifer-hardwood, eucalypts, rainforest, scrub and grassland). However, instead of using the maximum increase in water yield in the first five years after treatment, they used the average water yield changes in the first five years after treatment. Using fuzzy linear regression analysis, they concluded that for a 10% reduction in:

- conifer-type forest, water yield increased by 20-25mm;
- eucalypt forest, water yield increased by 6 mm;
- scrub, water yield increased by 5 mm; and
- deciduous hardwoods increased water yield by 17-19mm.

As expected these estimates are lower than those of Bosch and Hewlett (1982) where the maximum change in water yield in the first five years after treatment were used. The use of maximum increase will lead to higher estimate of the reduction in water yield as opposed to the same analysis performed with average increases. The use of maximum increase is also likely to be driven by climate variability as the maximum increase will generally correspond to the year of greatest rainfall. However, if average values are used the results are potentially impacted by regrowth vegetation after clearing and the adjustment time scales associated with vegetation changes.

Figure 2-1 shows the results of the Bosch and Hewlett (1982), Stednick (1996), Sahin and Hall (1996) plus the additional catchments included in this review. The predicted water yield changes from Bosch and Hewlett (1982), and Sahin and Hall (1996) are also depicted as dotted and solid lines respectively. The data have been divided into 4 broad vegetation types, conifers, eucalypts, hardwoods (these catchments are primarily from the Northern Hemisphere and include deciduous vegetation types) and scrub (remaining catchments, usually shorter vegetation types). Some of the within group variability shown in Figure 2-1 can be explained by the difference in mean annual rainfall (MAR) of the catchments. Figure 2–2 shows the results for each of the experiments (scaled to 100% of area treated) against the MAR. From a similar plot, Bosch and Hewlett (1982) concluded that water yield changes are greatest in high rainfall areas. The results for the different vegetation types for all studies in this review support this conclusion.
Figure 2–1: Water yield changes as a result of changes in vegetation cover from Bosch and Hewlett (1982), Sahin and Hall (1996) and Stednick (1996). Results from Bosch and Hewlett and Stednick represent the maximum increase in the first 5 years after treatment for deforestation, regrowth and forest conversion experiments or maximum change in water yield for afforestation experiments. The results from Sahin and Hall are the average increases in water yield in the first 5 years after treatment.

Figure 2–2: Distribution of water yield changes (scaled to 100% change in cover) as a function of mean annual rainfall for the studies shown in Figure 2–1.
While paired catchments provide a means of comparing the response of water yield to different treatments and vegetation types, methodologies are required that allow prediction of the effects of permanent changes in vegetation. These predictions have to be based on both available data and a good understanding of the processes impacted by the vegetation change.

The main process responsible for changes in water yield as a result of alterations in vegetation at the mean annual scale is evapotranspiration (Zhang et al., 2001; Holmes and Sinclair, 1986; Turner, 1991). Holmes and Sinclair (1986) used the relationship between mean annual evapotranspiration and mean annual rainfall to predict the increase in water yield when converting from forest to grass in a catchment. Their results were based on a series of catchments in Victoria, Australia. When assessing the mean annual changes in water yield, the storage change term in the water balance is small compared with the other terms, hence the change in runoff can be predicted from the change in evapotranspiration. Zhang et al. (1999, 2001) expanded on the work by Holmes and Sinclair (1986) by analysing results from 250 studies worldwide. Using a pair of curves to illustrate the difference in evapotranspiration under different vegetation types along a rainfall gradient, Zhang et al. (2001) developed a simple two-parameter model to estimate the mean annual evapotranspiration at the catchment scale for two broad vegetation types, forest and grass. Figure 2–3 shows the Zhang curves and the data points used to derive these generalisations. The difference between the grass and forest curve represents the change in mean annual water yield for a 100% change in vegetation for a given mean annual rainfall. It should be noted that both paired catchments and time-trend studies were used in the derivation of the Zhang curves.
Figure 2–4 provides a comparison of the expected water yield changes predicted by the Zhang curves and results from paired catchment studies. While paired catchment studies were used in the derivation of the Zhang curves, Zhang et al. used only mean annual values from periods when the catchments were considered to be in equilibrium. Zhang only included both the pre- and post-treatment data for one of the paired catchments (Coweeta 17) analysed here. Therefore, it was not considered necessary to remove common catchments for this comparison. There is general agreement between the model and the paired catchment results, particularly for the conifer and eucalypt catchments. The large amount of scatter in the hardwood (deciduous and mixed) catchments (Figure 2–2 and Figure 2–4) is primarily due to catchments from the Coweeta experimental watersheds. These catchments show a marked difference in response to vegetation change depending on the catchment’s aspect. Catchments with a polar (northern) aspect have nearly three times the water yield increase of catchments with an equatorial (southern) aspect (Swank et al., 1987). While the north facing catchments from Coweeta show good agreement with Zhang curves, the Zhang curves over-estimate the water yield change from the south facing catchments. The scrub catchments are representative of vegetation that falls into neither the grass nor the forest category but are an intermediate vegetation structure. As would be expected in these catchments the change in water yield is less than the predicted change when going from a grass to forested catchment.
In general, the Zhang curves produce larger estimates of the mean annual water yield change than is reported for paired catchment studies. This is to be anticipated as paired catchment studies generally relate to timber harvest or regrowth experiments (i.e. the catchments with an increase in yield in Figure 2–4). The results of regrowth experiments are generally reported as the maximum or average change in the first five years after treatment rather than the long term water yield change as predicted by the Zhang curves. The difference in the agreement between the paired catchment studies and the Zhang curves for different experimental types can also been seen in Figure 2–4. Afforestation with hardwoods and eucalypts show good agreement with the Zhang curves while the regrowth and deforestation experiments with the same vegetation types show smaller changes than those predicted by the Zhang curves. For conifers the Zhang curves under predict the increase in evapotranspiration due to afforestation, while deforestation and regrowth experiments showed good agreement. It should be noted that this comparison implicitly assumes that the response time of the paired catchments is short enough so that the observed changes in yield are representative of long term permanent changes in vegetation. As will be discussed further below, this is typically not the case for regrowth experiments.

In reviewing paired catchment studies both Stednick (1996) and Sahin and Hall (1996) state that difficulties occur when summarising the result of catchment experiments due
to the lack of certain key statistics from the reported results (Sahin and Hall, 1996) or insufficient detail of the site characteristics (Stednick, 1996). This may account for the lack of generalisation about the impacts of vegetation age on water yield and seasonal flows in previous review papers. While the information contained in previous reviews may be useful for determining the short term changes in water yield following vegetation change, it does not allow for the likely long term impact of permanent vegetation change or the inter- and intra-annual changes to be investigated. The mean annual relationships encapsulated in the Zhang curves provide a method to assess the impact of permanent vegetation changes on mean annual flows. However, they do not provide a method for assessing inter- or intra-annual variability or the time it takes a catchment to adjust to changes in vegetation type and reach a new equilibrium condition.

2.4 Annual water yield response time

A change of land-use in a catchment may lead to changes in its water balance components. The response time of streamflow is generally determined by climate (mostly rainfall), vegetation characteristics, catchment properties, and vegetation management practices. Response in streamflow will be slower following afforestation compared to deforestation as it takes time for trees to reach equilibrium water use. For example, streamflow usually will respond rapidly over a period of days or weeks following clearing or bushfire in a small headwater catchment. Typically, a catchment will take a number of years to adjust to vegetation changes, particularly where the vegetation itself develops over time. The response time can be defined as the time taken for the annual catchment yield to reach a new equilibrium state following a disturbance. Understanding of the response times is useful for water allocation policy and regional planning.

Using paired catchment data Hornbeck et al. (1993) looked at the long term effects of forest treatment on water yield in the USA under a range of climatic conditions. They found a variety of responses in water yield including:

- initial increases occur promptly after forest clearing;

- increases could be prolonged by controlling the regrowth (analogous with permanent vegetation change) - when regeneration of forest cover was permitted the increase in streamflow diminished rapidly in about 3 to 10 years; and
Chapter 2: Literature Review

- a small increase or decrease in water yield may persist for at least a decade.

Figure 2–5 shows the impact of vegetation changes for four catchments in the USA. The differing responses are consistent with our conceptual understanding based on the treatment undertaken; for example, in the Hubbard Brook experimental forest (HB2), 100% of the catchment was clear-cut and regrowth was then permitted. In this case an initial increase in water yield is observed (due to reduced interception and transpiration), as regrowth occurs the water yield increase is reduced. The observed reduction in water yield after about 15 years is due to the increased evapotranspiration of the regrowth compared to the old growth forest. The Marcell Experimental forest catchment (M4) shows a similar trend to Hubbard Brook, with an initial increase followed by a decline to pre-treatment levels. For the Fernow experimental forest (F7) the increase in water yield is more persistent than in Hubbard Brook. In the F7 catchment clearing was undertaken in two stages, the upper half of the catchment occurred in year 0 and the clearing of the lower half the catchment in year 4. Herbicides were applied to the catchment to prevent regrowth until year 7. After this point, the effect of the regrowth can again be seen with water yield returning to pre-treatment levels by year 27. The Leading Ridge Watershed research unit catchment (LR2) also shows the effect of a staggered treatment, with an increase in flows until the entire catchment was cleared in year 9 and herbicides applied in year 10. As regrowth occurs after the competition of the treatment the water yield returns to pre-treatment levels.
The regrowth experiments of the types shown in Figure 2–5 are useful for estimating the initial increase in water yield and the time taken for a catchment to return to its pre-disturbance state. However, they provide very limited information on the long-term impact of permanent vegetation changes that may occur under deforestation or afforestation, where the water yield will not return to pre-treatment conditions.

There are limited examples of paired catchment studies examining the impact of permanent vegetation changes on water yield. A number of paired catchment studies in south Western Australia have focused on the deforestation of native forest to be replaced by agriculture (Ruprecht and Schofield, 1989). Figure 2–6 shows the results of four different paired catchments in the Collie Basin in Western Australia. These catchments experience a Mediterranean climate with a mean annual precipitation ranging from 600 to 1400mm. Predominant pre-treatment vegetation in these catchments consists of jarrah (Eucalyptus marginata) and karri (Eucalyptus diversicolor). March Road, Yarragil 4L, Wights and Lemons catchments have mean annual rainfalls of 1050mm, 1120mm, 1200mm, 750mm respectively.
Looking at the results for the deforestation in the Wights catchment, it can be seen that an initial increase in water yield is observed in the first year after treatment (due to decreased interception and evapotranspiration). This is followed by a steady increase in water yield, as groundwater levels rise, until a new equilibrium is reached (Ruprecht and Schofield, 1989; Silberstein et al., 2003). The other deforestation catchments in Figure 2–6 (Lemons and Yarragil) have only been partially cleared and do not show an initial increase in water yield following treatment. Instead, these catchments show a steady increase in water yield over time. From the length of results reported in the literature, it is not possible to establish when they reached a new equilibrium condition. The results of clearing followed by regrowth in the March Road catchment show a similar trend to the regrowth in Hubbard Brook Catchment 2 USA (Figure 2–5) with an initial increase in water yield in the two years following treatment (due to reduced interception) followed by a return to pre-treatment levels in year 10.

The above results highlight the limitations of regrowth studies in predicting the long-term effects of permanent vegetation changes. It is clear that in many cases the initial increase after clearing is not always representative of the long-term increase as it may take several years for a catchment to reach a new equilibrium state. This is particularly important in the hardwood forest of North East USA and some eucalypt forests, where regrowth is primarily from the same root systems, making the changes in water yield...
short lived. However, regrowth experiments have the potential to be used to investigate the likely changes in evapotranspiration and streamflow with relation to forest age. This has been the focus of a number of paired catchment studies in southeastern Australia, where after clearing and subsequent regeneration, a decrease in water yield occurs. This decrease is due to the vigorous nature of the regrowth, which has a greater transpiration rate compared with old growth forests (Cornish and Vertessy, 2001; Vertessy et al., 2001; Roberts et al., 2001). Using paired catchment studies involving regrowth, it may be possible to predict the impact of afforestation or tree plantations on inter-annual water yield.

The Mountain ash forests in southern Australia provide an excellent example of this reduction in water yield following the regeneration of vegetation after bushfire. Mountain ash forests are confined to the wetter parts of Victoria and Tasmania and grow at altitudes of between 200 and 1000m, where mean annual rainfall exceeds 1200mm. Fire is an infrequent but vital component of the life cycle of these forests with the seedlings only growing on exposed soil with direct sunlight (Vertessy et al., 2001). Following fire, hundreds of seeds germinate per hectare, the intense competition between the plants for light results in rapid tree growth and natural thinning of weaker trees. There is a significant body of empirical evidence to show that the amount of water yield from these catchments is closely linked with stand age (Langford, 1976; Kuczera, 1987; Watson et al., 1999). The ‘Kuczera curve’ that describes the relationship between stand age and annual water yield is characterised by the following features (Vertessy et al., 2001):

- the mean annual water yield from large catchments covered with old growth mountain ash forest (>200 year) is approximately 1195 mm for regions where mean annual rainfall is ~1800mm;

- after burning and full regeneration of mountain ash forest the water yield reduces to 580mm at an age of ~27 years; and

- after 27 years of age the mean annual water yield increases and returns to pre-disturbance levels, taking as long as 150 years to fully recover.

The work by Cornish and Vertessy (2001) and Roberts et al. (2001) indicates that this may be a more general behaviour for eucalypt forests in Australia and does not only apply to mountain ash forests.
South Africa has the longest and most detailed record of paired catchment afforestation experiments, addressing permanent vegetation change from grassland to forest. Using data from South African afforestation experiments, Scott and Smith (1997) developed a series of generalised curves to predict the impact of afforestation on annual total flows and low flows as a function of plantation age, species planted, and site suitability as shown in Figure 2–7. The curves in Figure 2–7 are similar to those observed in Figure 2–6 (particularly for Wights catchment) indicating a similar type of response for both afforestation and deforestation experiments, with a period of transience being observed before a new equilibrium is reached. Figure 2–8 shows the comparison of annual results from deforestation and afforestation in areas of similar rainfall. The afforestation and deforestation experiments show that while a similar change in water yield is observed in the long term the time taken to reach this equilibrium is dependent on the treatment, with a new equilibrium being established more rapidly under deforestation than under afforestation.

![Figure 2–7: Generalised curves from estimating the percentage reduction in total and low flow after 100% afforestation with pine and eucalypt afforestation (after, Scott and Smith, 1997).](image)
Many of the paired catchment studies reported in the literature do not report long term changes and thus the generalisations about the time taken to reach a new equilibrium are limited. The models of Kuczera (1987) and Scott and Smith (1997) provide examples of predictive tools that can be used to look at the adjustment timescale associated with changes in vegetation. However, these models are limited in their applicability, with the Kuczera curve being specific to Mountain Ash forest and the Scott and Smith curves being specific to South Africa. While the Scott and Smith curves may be applicable to other parts of the world, the results indicate that in South Africa eucalypts use more water than pines. These results conflict with results from Australia, where pines are thought to use more water than eucalypts (Vertessy and Bessard, 1999).

2.5 Seasonal water yield

Our understanding of the vegetation impact on mean annual water yield is well advanced and there are robust methods available for predicting the impact of vegetation change on the mean annual water balance (Zhang et al., 2001). Methods have also been established that allow the prediction of water yield changes in response to vegetation change at the annual time scale (Kuczera, 1987; Scott and Smith, 1997). The effects of vegetation on seasonal, monthly and daily flows are less well understood. However, the impact of vegetation change on seasonal water yield can be as or more important than the impact on annual water yield. The analysis of paired
catchment data in the USA in the 1970’s and early 1980’s commonly used regression by least squares on both annual and monthly data (Hibbert, 1969; Hornbeck et al., 1987; Rich and Gottfried, 1976; Johnson and Kovner, 1956). This allowed the impact of annual water yield as well as seasonality to be assessed. However, no generalisations have been made on the responses in seasonal water yield to changes in vegetation. This may be due to the mainly qualitative and graphical nature of many of the seasonal flow results reported in the literature.

To gain a good understanding of the processes affecting water yield it is important to note that the annual streamflow and evapotranspiration do not tell the complete story because of seasonal interactions of factors affecting the water balance, such as soil moisture content (Johnson and Kovner, 1956). While on a mean annual basis the changes in soil moisture can be assumed to be negligible, this is not the case on a seasonal basis. This section aims to provide a qualitative summary of the impact of vegetation change on seasonal water yield. This has been achieved by reviewing papers reporting seasonal water yield changes and grouping the results into four broad categories based on climate. No attempt has been made to divide the results based on treatment or vegetation type. The climatic groupings adopted are tropical/summer dominant rainfall catchments, snow affected catchments, catchments with winter dominant rainfall, and catchments with uniform rainfall.

Table 2-1 provides a summary of the observed seasonal changes in water yield. When summarising seasonal responses a differentiation has been made between the absolute and proportional responses. Absolute responses refer to the total volume change, while proportional responses refer to the change with respect to the flow under the original vegetation type. The differences between absolute and proportional reductions have important management implications. While most of the water yield or volume change occurs during wetter months, the proportional responses vary considerably depending on the climate and treatment type.
### Table 2-1: Seasonal responses in water yield.

<table>
<thead>
<tr>
<th>Climate</th>
<th>Absolute response</th>
<th>Proportional response</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical/Summer dominant rainfall</td>
<td>Larger changes in summer months, when rainfall is greater than monthly average.</td>
<td>Two types of responses observed:</td>
<td>Blackie, 1979; Blackie and Edwards, 1979; Bruijnzeel, 1988; Bruijnzeel, 1990; Gafur et al., 2003; Sharda et al., 1988; Scott and Lesch, 1997; Van Lill et al., 1980.</td>
</tr>
<tr>
<td>Snow affected catchment</td>
<td>Largest changes in months of snow melt.</td>
<td>Larger change in summer growing season.</td>
<td>Baker, 1984; Troendle et al., 2001; Alexander et al., 1985; Troendle, 1983; Schnider and Ayer, 1961; Hornbeck et al., 1970; Hornbeck 1975</td>
</tr>
<tr>
<td>Winter dominant Rainfall</td>
<td>Largest changes in winter months when rainfall is above monthly average.</td>
<td>Largest change in summer months when rainfall is below monthly average.</td>
<td>Bari et al., 1996; Bren and Papworth, 1991; Burch et al., 1987; Caissie et al., 2002; Gallart et al., 2002; Keppeler and Ziemer, 1990; Kirby et al., 1991; Lewis et al., 2000; Mein et al., 1988; Miller et al., 1988; Rogerson, 1971; Rothacher, 1970; Ruprecht et al., 1991; Watson et al., 2001.</td>
</tr>
<tr>
<td>Uniform Rainfall</td>
<td>Uniform change across all seasons.</td>
<td>With deciduous vegetation there is a larger change during the spring months. Evergreen vegetation shows uniform change across all seasons.</td>
<td>Hibbert 1969; Johnson and Kovner 1956; Lane and Mackay, 2001; McLean, 2001; Swank et al. 2001.</td>
</tr>
</tbody>
</table>
In winter dominant rainfall catchments similar responses are seen in all studies, with a much larger proportional reduction the summer flows compared with the winter flows. This is mainly driven by the change in interception and evapotranspiration. In catchments with winter dominant rainfall the maximum potential evapotranspiration occurs during the period of lowest rainfall, i.e. the rainfall and potential evapotranspiration are out of phase. This results in highest demand for water by vegetation, when water availability is low. Under forests, there is a greater ability of the vegetation to extract water from soil moisture stores resulting in lower baseflow compared to grass catchments.

In summer dominant rainfall catchments the results can vary from uniform changes across all seasons (Sharda et al., 1998) to large changes in dry season flow (Edwards, 1979; Scott et al., 2000). These different responses can be seen from the results from the Glenmorgan research farm, India and Cathedral Peak, South Africa (Figure 2–9). Both of these catchments have summer dominant rainfall and have been afforested, however, the proportional changes in water yield are significantly different. The difference in responses observed in summer dominant rainfall catchments, undergoing similar changes in vegetation highlights the difficulties associated with making generalisations about the seasonal impacts on water yield. At the seasonal time scale other catchment characteristics such as soil depth and type play a much larger role in the response than on the mean annual basis.

![Figure 2–9: Average monthly reductions in streamflow from the Glendhu catchment (afforestation with pines 1980) and Cathedral Peak II, South Africa (afforestation 1950-1955), Glenmorgan research Farm, India. Value 1 – 12 on the x-axis represent the months January to December for Southern Hemisphere catchments and July to June in the Northern Hemisphere catchment.](image)
This difference in absolute and proportional response can be seen in results from the Glenmorgan research farm in India where Sharda et al. (1998) used a monthly average dataset to look at the seasonal nature of water yield changes. It was observed that the major reduction in mean annual flow caused by the blue gum (*Eucalyptus globulas*) plantation occurred during the months from July through to October, when 60% of the mean annual rainfall occurred. These results indicate that the major reductions in flow volume occur during the monsoon (July – October). However, it should also be noted that although the reduction in flow during the dry period was small on a volume basis compared with the wet season, the percentage reduction in flow is significant during all months of the year. The early and late monsoon periods show different responses in water yield change, which may be related to soil moisture dynamics introducing delays in response time.

A similar analysis was carried out on the Glendhu catchment in New Zealand, these results are also presented in Figure 2–9. These three examples illustrate different seasonal responses to afforestation in different climatic regions. The New Zealand example depicts a reasonably constant rainfall throughout the year coupled with a constant reduction in streamflow. The Indian and South African examples have highly seasonal rainfall; resulting in seasonal variation in the reductions in water yield.

As stated by Vertessy (1999), the information on the seasonal variations in water yield is limited and rather confusing. The way in which the data on seasonal yield are presented in the literature is generally descriptive or graphical, making it hard to generalise between the results of different studies. While on an annual basis the results of paired catchment studies seem to be easily generalised according to vegetation type, this is not the case for seasonal data.

### 2.6 Flow duration curves

While the magnitude of changes at the mean annual, annual and seasonal time steps are important, many water resources management issues require an understanding of the impact of vegetation on flow regime. A catchment’s flow regime is described by the magnitude, frequency, duration, timing and rate of change of streamflow at a given point. The impact of changing vegetation type on flow regime can be depicted by a catchment’s flow duration curve (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 (water abstractions, upstream reservoirs etc) and land-use type (Smakhtin, 1999).

FDCs can be constructed using multiple temporal scales of streamflow data: annual, monthly or daily flows, depicted either using all the flows for the period of record or flows from a particular year. Seasonal FDCs can also be constructed by using only flows for a particular season over the period of record or on an annual basis. For example, a daily annual FDC is constructed from daily flows for a single year, while a daily period of record FDC is constructed from daily flows for the period of record.

Ideally, comparisons between FDCs for different vegetation types would be made between daily period of record FDCs. These FDCs are more representative of catchment flows than daily annual FDCs. However, due to the limitations in length of data available for paired catchment studies it is often necessary to use daily annual FDCs for comparisons. One of the limitations of using daily annual FDCs 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, when making the comparison between daily annual FDCs it is important to compare years with similar precipitation to minimise the variations due to climate (Burt and Swank, 1992).

In discussing the impacts of vegetation change on flow regime, low and high flow need to be defined. The most widely used definition of low flow is any flow that is exceeded for 70 - 99% of the time (Smakhtin, 2001), hence this definition has been adopted. High or peak flows are taken here as the flows that are exceeded for 1 - 5% of the time.

The flow duration curves discussed below are daily annual FDC, and have been plotted for catchments in different climatic zones with differing vegetation changes. While data exists to plot such curves for a large number of catchments, only three examples that have previously been reported in the literature are discussed. These examples are the Red Hill catchment in south eastern Australia, where a pine plantation was established on pasture, Wights catchment in south Western Australia where pasture replaced native vegetation and the Glendhu catchment in New Zealand, where a pine plantation was established on tussock grassland.

Figure 2–10 depicts the change in flow regime for the Red Hill catchment in south eastern Australia. The catchment is located about 50 km west of Canberra, in the Murrumbidgee basin and is part of the paired catchment study looking at the impact of pine plantations on water yield. Red Hill has a catchment area of 195 ha and ranges in
altitude from 590 m to 835 m. The climate of the area is highly variable with a winter dominant rainfall. The mean annual rainfall is 876 mm (Hickel, 2001). FDCs for 1 and 8 year old pines (based on a water year from May to April) have been used to quantify the relative changes in the high and lows flows as a result of vegetation change. The 1 and 8-year old pines were chosen as these years have similar rainfalls, 887 and 879 mm respectively. The FDC indicated that there is approximately a 50% reduction in high flows while there is 100% reduction in low flows, with all flows in the designated low flow range ceasing once the pine plantation is well established.

Figure 2–10: Flow Duration curves for the Red Hill catchment, near Tumut, New South Wales, Australia. 1 year old pines and 8 year old pines (after Vertessy, 2000).

Figure 2–11 depicts the response to conversion of native forest to pasture in the Wights catchment in south Western Australia. As discussed in Section 2.4 the Wights catchment is part of a series on paired catchment studies in southwest Western Australia. In these catchments, the interplay between the local groundwater flow system and vegetation plays an important role in the hydrological response. The replacement of native forests by pastures in these catchments has lead to a rapid increase in groundwater discharge area (Schofield, 1996), resulting in large increases in low flows. As with Figure 2–10, it can be seen that all sections of the flow regime are affected by the change in vegetation. Comparing the FDC for native vegetation (1974-1976) with a period of similar climatic conditions of pasture (1983-1985) we observe a 50% reduction in high flows when going from pasture to forest and a 100% reduction in low flows.
Figure 2–11: Flow Duration curves for the Wights catchment in south Western Australia. (Based on a water year from April to March).

Figure 2–12 depicts the FDC response to the establishment of pine plantations in the Glendhu experimental catchments in New Zealand (169°45'E, 45°50'S). The control and treated catchments have mean annual rainfalls of 1310 mm and 1290 mm respectively. The treatment involved the planting of 67% of the catchment with *Pinus radiata* (McLean, 2001). The results from Glendhu show a different response in the FDC compared to Figure 2–10 and Figure 2–11. Unlike the Red Hill and Wrights catchments the control and treated FDC are similar during the calibration period. Therefore, the changes in high and low flows have been assessed through comparing the control to the treated catchment at various stages after treatment. The reductions in low and high flows are similar for all sections of the FDC with an approximate thirty percent reduction in both low and high flows as a result of the vegetation change. This response is typical of many catchments in higher rainfall areas, including the Mountain Ash catchments in Victoria (Watson *et al.*, 1999) and the Biesievlei catchment in South Africa.
Figures 2-10 to 2-12 depict two possible responses in flow regime as a result of vegetation change. The response seen in the Red Hill and Wights catchments are typical of areas where the annual actual evapotranspiration of forests approaches annual precipitation, while the response seen in Glendhu is typical of areas where annual precipitation is greater than the annual potential evapotranspiration. In the Mountain Ash catchments in southern Australia, Watson et al. (1999) noted that in wetter catchments all flows respond to climatic and vegetation changes in unison with the changes in the mean flow, however in the drier parts of their study area changes in low flows are accentuated.

As with the assessment of mean annual and annual flow, the annual FDC does not show how the flow regimes of different seasons are impacted. Analysing seasonal FDCs can overcome this limitation. However, few papers report seasonal FDCs. Hornbeck et al. (1997) looked at both annual and seasonal flows for the first year after clear felling in the Hubbard Brook experimental forest. Separating annual water yield change into changes during the growing (full leaf area) and dormant seasons (minimum leaf area) allowed investigation of the FDC response during periods of maximum evapotranspiration and periods of minimum evapotranspiration. Hornbeck et al. (1997) observed that most of the increase in annual yield occurred during the growing season as shown in Figure 2–13. They concluded that water yield increases
were a result of decreased transpiration and primarily occurred as augmentation to low flows during the growing season (Figure 2–13). While this seasonal break-up is obvious for deciduous catchments, the definition of seasons is less obvious for evergreen vegetation or catchments with uniform climate.

![Flow duration curves for the first year after the clear-felling treatment – Hubbard Brook experimental forest (after Hornbeck et al., 1997).](image)

Using a similar approach to the analysis of Hornbeck et al. (1997), McLean (2001) produced FDCs during winter (July – September) and summer (December – February) seasons where vegetation was converted from tussock to pine plantations in New Zealand. McLean (2001) concluded that:

- differences were more variable in summer flows than in the winter. This was due to the high variability in the rainfall over the summer months; and
- the seasonal effects of vegetation modifications are not easily identified using flow duration curves.

The difference in the results between Hornbeck et al. (1997), who found notable seasonal differences, and McLean (2001), who could not detect seasonal changes, can be attributed to the deciduous nature of the vegetation in the USA compared with the evergreen vegetation of the pine plantations in New Zealand. The distinct dormant season in the USA where there are no leaves on the trees results in lower interception...
and transpiration rates making the evapotranspiration rates of forested areas very similar to those of short crops. As with the mean seasonal responses discussed in Section 2.5, the response of the seasonal FDC to vegetation change will also differ depending on the rainfall pattern. The comparison between the annual FDCs for Red Hill (Figure 2–10) gives us some indication of the likely impact of pine plantation on the seasonal FDCs in this catchment. It would be anticipated that a larger proportional reduction in low flows in the Red Hill catchment indicates a larger change in the summer FDC, compared to the winter FDC as the majority of low flows occur during the summer months.

Jones and Grant (2001) noted that the nature of the analysis undertaken could influence the results. This was illustrated by the original analysis of peak flow responses to clear cutting and roads in small and large basins, western Cascades (Jones and Grant, 1996) and the subsequent reanalysis of the same data by Thomas and Megahan (1998), where the use of differing methods on the same data set yielded different results. The interpretation of the results from the two analyses has resulted in Jones and Grant (2001) concluding both analyses showed that forest harvest has increased peak discharges in small events by as much as 50% and by as much as 100% in large events. Thomas and Megahan (2001) agreed that peak flow increases (of up to 100%) in small events may occur, but argued that no evidence existed to suggest that this was the case for all event sizes including large floods.

2.7 Discussion

During the review of literature three major limitations were highlighted in relation to the previous analyse of paired catchment data. These are:

- generalisations about annual increases in water yield (Bosch and Hewlett, 1982; Stednick, 1996; Salin and Hall, 1996) are based on short term results of regrowth experiments (maximum change in the first five years after treatment, or first year increases). The results of permanent vegetation change experiments indicate that, depending on the changes in soil storage and the transpiration-vegetation age characteristics of the new vegetation type, it takes longer than 5 years for a new hydrologic equilibrium to be established;

- changes in vegetation type will affect not only mean annual flow, but also the variability of annual flow. Peel et al. (2001) noted that differences in the variability of annual runoff were due to two factors, the variability of annual precipitation and the distribution of evergreen and deciduous vegetation; and
in order to make quantitative generalisation about the impacts of vegetation changes on seasonal water yield, a method needs to be established that can be applied to a large number of catchments, so that when comparing results between sites, the generalisations are not complicated by conflicting results from different analytical methods.

Paired catchment studies provide a useful method for determining the relationships between percentage vegetation change and water yield in relatively small catchments. The results summarised in this paper indicate that for any impact of vegetation change to be detected, at least 20% of the catchment needs to be treated (Bosch and Hewlett, 1982). This result is derived from the research on small experimental catchments with typical record lengths of less than 10 years following treatment and longer records may mean that smaller changes can be detected. However, methods are needed for scaling these results to larger catchments where the area subject to vegetation change is likely to be patchy and relatively small compared to the overall catchment size. A few studies have attempted to make estimates of mean annual water yield change in larger catchments.

Munday et al. (2001) developed a model to simulate the temporal changes in streamflow associated with afforestation of existing grassland and the subsequent management of the forest for timber harvesting for the Adjungbilly catchment (389 km$^2$) in New South Wales using results from paired catchment studies of Red Hill (for pine plantations) and Karuah (for eucalypt forest). The analysis of data in the Adjungbilly catchment indicated that streamflow changes due to timber harvesting are statistically insignificant. However, in applying the model based on the paired catchment data to the Adjungbilly catchment, Munday et al. were able to simulate the magnitude and nature of the changes in mean annual yield from the catchment given the historical changes in vegetation type. This may indicate that results from paired catchment studies can be extrapolated to larger catchments. Scott et al. (1998) used the generalised curves of Scott and Smith (1997) for annual reduction in water yield, to determine the likely change in water yield on total runoff and low flows at regional scale as a result of afforestation in South Africa. This is the best example of prediction of water yield changes at a regional scale at the annual time scale.

The two examples above show how generalisations from small catchment experiments are being extrapolated to a regional scale and how treatments that cover less than 20% of the catchment might impact on water yield. It is worth noting that a potentially significant scale effect relates to the change in geomorphology as one move from
upland catchments to lowland catchments. In current applications to larger scales it is assumed that these different areas of the landscape react similarly to change in vegetation.

One of the advantages of paired catchment studies is that they remove climate variability through the comparison of two catchments subject to the same climatic conditions under different land uses. The separation of climatic variability effects from the water yield changes as a result of vegetation alterations is a key problem for time trend studies. In cases where paired catchments are available, the separation of land use impacts from climatic factors can be achieved through the comparison of the two catchments. This can be done not only for annual and mean annual totals, but also for flow regime as depicted by the daily annual flow duration curves in Figure 2-10 to 2-12. There is also the potential to use paired catchments to determine the seasonal impacts of vegetation change.

### 2.8 Summary

The previous reviews of paired catchment studies have focused mainly on regrowth experiments. In such studies, changes in water yield are only observed in the first couple of years following treatment before returning to pre-treatment levels. This paper has focused on the application of paired catchment results to the prediction of different aspects of hydrologic response to permanent vegetation change. Firstly, the changes in mean annual yield documented in previous paired catchment reviews were compared with the mean annual water balance model of Zhang et al. (2001). This analysis indicated good agreement between the paired catchment and the mean annual water balance approach. A comparison of the long term annual results of regrowth, deforestation and afforestation experiments indicated that following permanent changes in vegetation it takes more than five years for a catchment to reach a new equilibrium, with deforestation experiments reaching a new equilibrium earlier than afforestation experiments. The transient nature of the water yield changes makes the use of regrowth experiments for predicting the impacts of permanent vegetation changes on water yield questionable. Table 2-2 provides a summary of the uses and limitation of paired catchments for predicting permanent changes in vegetation at different temporal scales.

This review highlights the lack of information available in the literature for making quantitative generalisations about the impacts of vegetation changes on seasonal yield and flow regime. While the effect of vegetation change on a mean annual basis is well
understood the research on seasonal water yield reported in the literature is limited and primarily of a descriptive or graphical nature making quantitative generalisations difficult. While many papers on individual paired catchment studies report seasonal results it was not considered possible to make quantitative predictions, due to the qualitative or graphical nature of many of the results presented. The papers reporting seasonal results were grouped by climate and some broad generalisation made. In all catchments, the largest volume changes occur during the wet periods with small volume changes during the dry periods. The main difference between catchments came in the proportional reductions. Nearly all winter dominant and snow affected catchments showed larger proportional changes in dry summer months compared to the wet winter months. In tropical catchments two types of responses where observed, with either a uniform proportional change in water yield in all seasons or a greater proportional change in dry season flow. Catchments with uniform rainfall tended to show more uniform reductions in water yield across all seasons.

As a means of gaining an understanding of the impact of vegetation change on flow regime, the FDC was used as a means of displaying the complete range of daily flows over a given time period. While insufficient data were available for making generalisations about the FDC response to vegetation change, the three examples used highlight this as a useful method of assessing the likely impact of vegetation on daily flows that requires further exploration.

This thesis addresses two of the knowledge gaps identified in this literature review. The first of these is the need for consistent analysis of paired catchment data to allow better comparison of results between sites. This consistent analysis is performed on 46 paired catchment studies for both annual streamflow and FDCs in Chapter 4. The second knowledge gap to be addressed is the need for predictive methodologies for periods shorter than the mean annual time scale. This is addressed in Chapters 5 and 6, via the development of a method to adjust a catchment’s FDC for a change in forest cover.
Table 2-2: Summary of results from paired catchment studies, highlighting the limitation and uses of the transient vegetation studies (regrowth and forest conversion experiments) and permanent vegetation studies (afforestation and deforestation experiments) for making generalisation at different timescales and list references for predictive tools currently available

<table>
<thead>
<tr>
<th>Time Scale</th>
<th>Summary of results</th>
<th>Generalisations/ predictive models</th>
</tr>
</thead>
</table>
| Mean Annual    | • Bosch and Hewlett’s (1982) estimations may underestimate the impacts of permanent vegetation changes due to use of maximum increase in the first five years after treatment.  
• Zhang curves provide a good predictive tool for estimating the change in water yield between grass and forested catchment. However, no differentiation is made between tree species.  
• Results of comparison between paired catchment results and Zhang curves indicate that under afforestation, conifers tend to use more water than hardwoods or eucalypts. | Bosch and Hewlett, 1982; Vertessy and Bessard, 1999; Zhang et al., 2001. |
| Annual         | • Water yield changes over time until a new equilibrium is reached following permanent alteration to vegetation in a catchment.  
• It may take several decades for a catchment to reach equilibrium under new vegetation type or to return to pre-treatment levels following fire or forest harvesting.  
• Regrowth and forest conversion experiments do not show the same extent of water yield change as deforestation and afforestation experiments | Kuczera, 1987; Scott and Smith, 1997; |
| Seasonal       | • Generalisations about seasonal water yield are difficult to make based on the reported literature due to different definitions of seasons and the graphical and descriptive nature of the results.  
• Based on climate groups, different seasonal responses are observed. Tropical or summer dominant rainfall catchments show larger absolute changes in the wet season, while proportional changes are either similar during all seasons or greater during the winter months. Winter dominant rainfall catchments show largest absolute responses in the winter season, while larger proportional reductions are observed during the summer months. | Scott and Smith, 1997 |
| Flow Duration  | • Provide a useful means of displaying the complete range of daily flows.  
• Allow the impacts on low and high flows to be assessed at different temporal scales (annual or seasonal)  
• Seasonal flow duration curves can be used to assess the seasonal impacts on daily flows. | - |
| Curves         |                                                                                                                                            |                                     |
CHAPTER 3 Data Description

3.1 Introduction
Chapter 2 provided a review of paired catchment studies. This review highlights a need to not only understand and interpolate the results from individual paired catchment studies but also a need to be able to generalise the results and make predictions about the impacts of vegetation changes on streamflow. This predictive capability is required, as many water managers need to be able to not only understand the likely impact of changes in forest cover on streamflow, but they also need to make predictions about the magnitudes of any changes. The need to predict the magnitude of the change is driven by a requirement to assess the impact of vegetation changes, such as an increase in plantation forestry, on all water users in the catchment. The change in forest cover in a catchment can potentially affect the amount of water leaving a catchment as runoff due to changes in evapotranspiration. While it is currently possible to predict the changes in evapotranspiration, and hence streamflow at the mean annual scale (Zhang et al., 1999; 2001; 2004), methodologies are required that allow predictions to be made at shorter time scales.

In order to develop predictive models for a shorter timescales, data at shorter timescales are required. In the development of the mean annual streamflow prediction models of Zhang et al. (1999; 2001; 2004), data from any catchment under a stable land use were used. However, in order to develop models at shorter time scales, data are required that allow the variations in climate to be separated from changes or trends in streamflow due to changes in forest cover. This thesis focuses on the use of paired catchment data as a means to understanding the impacts of permanent changes in forest cover on a catchment’s daily flow duration curve (FDC). Paired catchment studies assessing the impact of permanent changes in vegetation are used to develop and test a predictive model that allows a catchment’s FDC to be adjusted for the impacts of changes in forest cover.

This chapter provides a description of the paired catchment studies used in chapters 4 to 6 of this thesis, as well as a description of an additional experimental catchment used to test the predictive FDC model described in chapters 5 and 6.

3.2 Types of experimental catchments
Two types of experimental catchments have been used in this thesis, paired catchments studies and single experimental catchments. The major difference between these two types of experimental catchments is the presence of a control
catchment in the paired catchment studies. This control catchment allows the effect of climate variability on streamflow to be separated from the impact of vegetation changes. Therefore, paired catchments studies make up the majority of the catchments used in this thesis and are classified by treatment type. Four types of treatment have been identified. These are regrowth experiments, deforestation experiments, afforestation experiments and forest conversion experiments. Detailed descriptions of these treatments were outlined in Chapter 2.

All types of paired catchment studies have been used in the analysis undertaken in Chapters 4 and 5, while only the paired catchment studies with permanent changes in vegetation have been used in the development of the predictive models described in Chapter 6.

3.3 Brief Description of experimental catchments

Figure 3–1 shows the location of the experimental catchments used in this thesis. In total 46-paired catchment studies have been used, each of them is described briefly below with the key references where detailed information about these studies can be found. The description of the paired catchment studies has been grouped by the type of treatment. The majority of experimental catchments considered in this thesis are Australian. However, data were also obtained from South African, New Zealand, United States of America and the United Kingdom.
The descriptions of the catchments used in this thesis include details of location, the type and date of treatment and the length of the record available.

3.3.1 Regrowth experiments

Regrowth experiments are the most common paired catchment studies. These involve the clearing or partial clearing of a catchment followed by regeneration with the same vegetation type that was previously present in the catchments. These studies have been widely used to gain an understanding of the impact of vegetation age on streamflow. In total, data from 29 regrowth experiments have been acquired for use in this thesis.

Maroondah experimental catchments, Victoria, Australia


Data from seventeen small experimental catchments within the Maroondah study area have been obtained for use in this project. All of the treated catchments within the study area have been subjected to a treatment followed by regeneration of the similar vegetation, thus all treated catchments can be classified as regrowth experiments. The seventeen catchments that make up the Maroondah study area can be divided into five smaller experimental groupings: Black Spur, Ettercon, Myrtle, Monda, and Coranderrk.

The Black Spur group consists of three treated catchments (Black Spur 1, 2 and 3) and one control catchment, Black Spur 4. The mean annual rainfall of these catchments is 1662mm. The catchments are covered predominately in mountain ash (*Eucalyptus regnans*), the majority of which is regrowth resulting bushfires that occurred in 1939. The original research objectives were to determine the effect of thinning and patch cutting in catchments already under regrowth. Table 3-1 provides details of the treatments carried out in each catchment, along with some basic catchment information.
Chapter 3: Data Description

Table 3-1: Description of Black Spur Experimental Catchments

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Treatment</th>
<th>Pre-treatment vegetation</th>
<th>Length of record available Pre-treatment</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Spur 4</td>
<td>9.8</td>
<td>Control</td>
<td>E. Regnans</td>
<td>Jun 1970 to Oct 1986</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Like the Black Spur group, the Ettercon experimental catchments consist of one control and three treated catchments. The catchments were burnt in the 1939 bushfires and the pre-treatment vegetation is regrowth *E. regnans*. The mean annual rainfall in the Ettercon catchments is approximately 1250 mm/year. Table 3-2 provides details of the treatments carried on each of the catchments. In addition to the treatments described in Table 3-2, all four Ettercon catchments were infested by the disease Psyllids in 1988. This disease reduces leaf area. This results in reduced water use by vegetation and which increases streamflow.

Table 3-2: Description of Ettercon Experimental catchments

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Treatment</th>
<th>Pre-treatment vegetation</th>
<th>Length of record available Pre-treatment</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ettercon 3</td>
<td>15.01</td>
<td>Control</td>
<td>E. Regnans</td>
<td>Jul 1971 onwards</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The three treated groups in the Monda catchments were all clear-felled followed by burning and planting of seedlings. The pre-treatment vegetation is regrowth *E. regnans* resulting from the 1939 bushfires. The mean annual rainfall in these catchments is 1800 mm/year. In addition to the treatments listed in Table 3-3 these catchments were also infested in Psyllids in 1988 and again in 1996.
Chapter 3: Data Description

Table 3-3: Description of Monda Experimental catchments

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Treatment</th>
<th>Pre-treatment vegetation</th>
<th>Length of record available Pre-treatment</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monda 1</td>
<td>6.31</td>
<td>79% clearfelled</td>
<td>E. Regnans</td>
<td>Jun 1970 to Dec 1977</td>
<td>May 1978 onwards</td>
</tr>
<tr>
<td>Monda 2</td>
<td>3.98</td>
<td>75% clearfelled</td>
<td>E. Regnans</td>
<td>Jun 1970 to Dec 1977</td>
<td>May 1978 onwards</td>
</tr>
<tr>
<td>Monda 3</td>
<td>7.25</td>
<td>80% clearfelled</td>
<td>E. Regnans</td>
<td>Jun 1970 to Dec 1977</td>
<td>May 1978 onwards</td>
</tr>
<tr>
<td>Monda 4</td>
<td>6.31</td>
<td>Control</td>
<td>E. Regnans</td>
<td>Jun 1970</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The Myrtle experimental group consists of one control and one treated catchment. Unlike the Monda, Ettercon and Black Spur, the Myrtle experimental catchments were not burnt in the 1939 bushfires, thus the dominate vegetation cover in these catchments is old growth Mountain ash (*E. regnans*). The mean annual rainfall in these catchments is 1600 mm/year. Myrtle 2, the treated catchment, was clear-felled and then seeded. In addition to the treatments described in Table 3-4, the two Myrtle catchments were subjected to Psyllid infestation in 1996.

Table 3-4: Description of Myrtle Experimental catchments

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Treatment</th>
<th>Pre-treatment vegetation</th>
<th>Length of record available Pre-treatment</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Myrtle 1</td>
<td>25.21</td>
<td>Control</td>
<td>E. Regnans</td>
<td>Apr 1972 onwards</td>
<td>N/A</td>
</tr>
<tr>
<td>Myrtle 2</td>
<td>30.48</td>
<td>74% clearfelled</td>
<td>E. Regnans</td>
<td>Jul 1971 to Dec 1984</td>
<td>1985 onwards</td>
</tr>
</tbody>
</table>

The Coranderrk experimental group consists of one control and two treated catchments. The pre-treatment vegetation in these catchments is much older than the catchments in the North Maroondah catchments group, with the *E. regnans* dating to 1850. Unlike the Northern Maroondah catchments, the pre-treatment vegetation consists of a mixture of *E. regnans* and *E. oblique*. The mean annual rainfall in these catchments is 1440 mm/year.
Chapter 3: Data Description

Table 3-5: Description of Coranderrk Experimental catchments

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Treatment</th>
<th>Pre-treatment vegetation</th>
<th>Length of record available</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Picaninny</td>
<td>52.8</td>
<td>78% clearfelled</td>
<td>E. Regnans, E. obliqua</td>
<td>Mar 1956 to Nov 1971</td>
<td>Apr 1972 onwards</td>
</tr>
<tr>
<td>Slip</td>
<td>62.3</td>
<td>Control</td>
<td>E. Regnans, E. obliqua</td>
<td>Jul 1955 onwards</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Tantawangalo Creek, New South Wales, Australia

Key Reference: Lane and Mackay, 2001

Streamflow data were collected for a period of 11 years at the Tantawangalo Creek Site, with the aim of assessing the effect of differing logging practices on streamflow in mixed eucalypt forest. The mean annual rainfall of site is 1100 mm. Table 3-6 provides details of the three catchments in this experimental group.

Table 3-6: Description of the Tantawangalo Creek catchments

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Treatment</th>
<th>Pre-treatment vegetation</th>
<th>Length of record available</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceb</td>
<td>21.7</td>
<td>Control</td>
<td>Open sclerophyll forest</td>
<td>1987 – 1997</td>
<td>N/A</td>
</tr>
<tr>
<td>Wicksend</td>
<td>68.2</td>
<td>38% patch cut</td>
<td>Open sclerophyll forest</td>
<td>1987 – 1989</td>
<td>1990 - 1997</td>
</tr>
<tr>
<td>Willbob</td>
<td>85.6</td>
<td>30% selective logging</td>
<td>Open sclerophyll forest</td>
<td>1987 – 1989</td>
<td>1990 - 1997</td>
</tr>
</tbody>
</table>

Yambula State Forest, New South Wales, Australia

Key References: MacKay and Cornish, 1982; Moore et al., 1986; Crapper et al., 1989; Roberts, 2001; Roberts et al., 2001

The Yambula State Forest is located approximately 30km from the southeast coast of New South Wales. The pre-treatment vegetation in the Yambula State forest consists of a dry sclerophyll forest, having a tall open structure dominated by *Eucalyptus seeberi* (~40% of trees), *E. agglomerate* (~20% of trees) and *E. muellerana* (~10% of trees). The mean annual rainfall is ~900 mm and is highly variable. Data from four experimental catchments in Yambula State Forest have been used in this project, three treated catchments and one control catchment as described in Table 3-7.
Table 3-7: Description of Yambula state forest experimental catchments (Roberts, 2001)

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Treatment</th>
<th>Pre-treatment vegetation</th>
<th>Length of record available</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pomaderris Creek</td>
<td>75.9</td>
<td>Control Catchment</td>
<td>dry sclerophyll forest</td>
<td>1977 – 1999</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>January - April 1987: Integrated harvesting</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>June - July 1987: Post logging burn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>May 1978 – Jan 1979: Integrated harvest 36% of area</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>January 1979: Wildfire (100% burnt)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>January 1979: Wildfire (80% severely burnt, 10% lightly burnt, 10% unburnt)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>June – December 1979: Salvage logging (86% of area)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

HJ Andrews, Coyote Creek, Fox Creek, Oregon, USA

Key References: Rothacher, 1970; Jones 2000.

The HJ Andrews experimental forest is located in the central Cascade Range of Oregon. The pre-treatment vegetation in the catchment is dominated by old growth Douglas Fir. The mean annual precipitation of the region is 2290mm/year, with wet winters and dry summers. Data from ten catchments have been obtained, seven treated catchments and three control catchments. Details of these catchments can be found in Table 3-8. Coyote Creek and Fox Creek are also located in Oregon. Coyote Creek has a mean annual rainfall of 1230 mm/year and has three-treated catchments. Details can be found in Table 3-9. Table 3-10 shows the details of the Fox creek experimental catchments. Fox Creek has a mean annual precipitation of 2730 mm/year.
### Table 3-8: Description of the HJ Andrews experimental catchments

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Treatment</th>
<th>Pre-treatment vegetation</th>
<th>Length of record available Pre-treatment</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>HJA1</td>
<td>95.9</td>
<td>100% clear cut</td>
<td>Old growth Douglas fir</td>
<td>1953 - 1962</td>
<td>1963 - 2004</td>
</tr>
<tr>
<td>HJA2</td>
<td>60.3</td>
<td>Control</td>
<td>Old growth Douglas fir</td>
<td>1953 - 2004</td>
<td>N/A</td>
</tr>
<tr>
<td>HJA6</td>
<td>13.0</td>
<td>100% clear cut</td>
<td>Old growth Douglas fir</td>
<td>1964 - 1973</td>
<td>1974 - 2004</td>
</tr>
<tr>
<td>HJA8</td>
<td>21.4</td>
<td>Control</td>
<td>Old growth Douglas fir</td>
<td>1964 - 2004</td>
<td>N/A</td>
</tr>
<tr>
<td>HJA9</td>
<td>8.5</td>
<td>Control</td>
<td>Old growth Douglas fir</td>
<td>1969 - 2004</td>
<td>N/A</td>
</tr>
<tr>
<td>HJA10</td>
<td>10.1</td>
<td>100% clear cut</td>
<td>Old growth Douglas fir</td>
<td>1969 – 1974</td>
<td>1975 - 2004</td>
</tr>
<tr>
<td>Mack Creek</td>
<td>581</td>
<td>15% clear cut and salvage logged</td>
<td>Old growth Douglas fir</td>
<td>No pre-treatment (treatment in 1962)</td>
<td>1980 - 2004</td>
</tr>
</tbody>
</table>

### Table 3-9: Description of the Coyote Creek experimental catchments

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Treatment</th>
<th>Pre-treatment vegetation</th>
<th>Length of record available Pre-treatment</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coyote 4</td>
<td>49</td>
<td>Control</td>
<td>Douglas fir, mixed conifers</td>
<td>1963 - 2001</td>
<td>N/A</td>
</tr>
</tbody>
</table>
### Table 3-10: Description of the Fox Creek experimental catchments

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Treatment</th>
<th>Pre-treatment vegetation</th>
<th>Length of record available</th>
<th>Pre-treatment</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fox Creek 2</td>
<td>253</td>
<td>Control</td>
<td>Douglas Fir, western hemlock</td>
<td>1958 - 1988</td>
<td></td>
<td>N/A</td>
</tr>
</tbody>
</table>

#### 3.3.2 Forest conversion experiments

Only two forest conversion experiments have been collected as part of this data set, one from Australia and one from South Africa. Forest conversion involves the change in vegetation type from one forest type (generally native) to another (generally plantation).

**Stewarts Creek, Victoria, Australia**

Key References: Mein *et al.*, 1988; Nandakumar, 1993

The Stewarts creek experiment is the only forest conversion experiment for which daily data were obtained. The original catchment study consisted of two treated and two control catchments. One experimental pair looked at the conversion from mixed Eucalypt forest to pasture while the other looked at the conversion of mixed Eucalypt forest to Pine plantation. Only the mixed Eucalypt to pine plantation experiments have been used in this thesis. This is because there appears to be groundwater leakage between the control and the treated experiments in the eucalypt to pasture experiment. Details of the Eucalypt to pine plantation experiment are shown in Table 3-11.
### 3.3.3 Deforestation experiments

Deforestation experiments involve conversion of densely vegetated land to grass or pasture. Data from five deforestation experiments have been collated for use in this thesis. Three are located in the Collie River Basin, Western Australia, while the remaining catchments are located in South Africa.

**Collie Catchments, Western Australia.**


The five experimental catchments in the Collie River Basin, south of Perth were set up in the early 1970’s. The experiments were established to assess the impact of clearing on streamflow and salinity. A pair of catchments (Salmon and Wights) were instrumented in a relatively high rainfall area (~1100 mm/year), while three catchments were established in a medium rainfall environment (~700 mm/year). The treated catchments were cleared in the summer of 1976/1977. Details of the experimental catchments are presented in Table 3-12.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Treatment</th>
<th>Pre-treatment vegetation</th>
<th>Length of record available</th>
<th>Pre-treatment</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA5</td>
<td>17.6</td>
<td>Conversion to Pine plantation</td>
<td>Mix species Eucalypt</td>
<td>1960-1969</td>
<td>1970 onwards</td>
<td></td>
</tr>
<tr>
<td>CA4</td>
<td>25.3</td>
<td>Control</td>
<td>Mixed species Eucalypt</td>
<td>1960 onwards</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

*Table 3-11: Description of the Stewarts Creek catchment experiment*
Table 3-12: Description of the Collie River Basin experimental catchments

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Treatment</th>
<th>Pre-treatment vegetation</th>
<th>Length of record available Pre-treatment</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Don</td>
<td>350</td>
<td>40% strip and parkland clearing</td>
<td>Native eucalypt forest</td>
<td>1974-1976</td>
<td>1977-1997</td>
</tr>
<tr>
<td>Lemon</td>
<td>346</td>
<td>54% cleared</td>
<td>Native eucalypt forest</td>
<td>1974-1976</td>
<td>1977-1997</td>
</tr>
<tr>
<td>Ernie</td>
<td>268</td>
<td>Control</td>
<td>Native eucalypt forest</td>
<td>1974 - 1997</td>
<td>N/A</td>
</tr>
<tr>
<td>Wights</td>
<td>93</td>
<td>100% cleared</td>
<td>Native eucalypt forest</td>
<td>1974-1976</td>
<td>1977-1997</td>
</tr>
<tr>
<td>Salmon</td>
<td>83</td>
<td>Control</td>
<td>Native eucalypt forest</td>
<td>1974 - 1997</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Witklip, South Africa

Key Reference: Scott et al., 2000

The Witklip experimental catchments are located in Mpumalanga Province and have a mean annual rainfall of 1005mm. Witklip has a humid sub-tropical climate with predominately summer rainfall. The two Witklip catchments were not planned as deforestation experiments, but large areas of the original plantings (1940’s) were cleared when the trees (both pines and eucalypts) were well established. Replanting did not happen immediately after the clearing, thus making it possible to use these catchments as deforestation experiments. Table 3-13 provides details of the treatments in the two Witklip catchments for which data are available. Unfortunately, no data were available for the control catchment, so the Witklip experiments have only been used in the analysis undertaken in Chapters 5 and 6 where no control data are required.

Table 3-13: Description of the Witklip experimental catchments

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Treatments</th>
<th>Pre-treatment vegetation</th>
<th>Length of record available Pre-treatment</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Witklip 5</td>
<td>108</td>
<td>51% felling of plantation</td>
<td>52% afforested, 48% grassland</td>
<td>1975 – 1978</td>
<td>1979 - 1990</td>
</tr>
<tr>
<td>Witklip 6</td>
<td>165.3</td>
<td>65% felling of plantation</td>
<td>74% plantation, 36% grassland</td>
<td>1975 – 1978</td>
<td>1979 - 1990</td>
</tr>
</tbody>
</table>
3.3.4 Afforestation experiments

The focus of this thesis is the development of a predictive model for permanent changes in land use. Data from afforestation experiments have provided the main source of information about these changes. Data have been obtained for 12 afforestation studies. Along with the deforestation experiments, these data form the basis for the testing of the predictive model described in Chapter 6.

Red Hill, New South Wales, Australia
Key Reference: Hickel, 2001

The Red Hill catchment and its control, Kylie’s Run, are located northeast of Tumut in New South Wales. Prior to the area being acquired by State Forests of New South Wales, both catchments were used for grazing and the vegetation consisted primarily of perennial pasture. In 1988 ~50ha of the Red Hill catchment was converted to pine plantation with the remaining area (~145ha) converted in 1989. In the areas along the drainage lines, many of the pines did not survive due to intolerance of the pines to the shallow groundwater table. By 1997, only 78% of the catchment was covered with pine. Table 3-14 describes the Red Hill and Kylie’s Run catchments. The Red Hill experimental catchment has a mean annual rainfall of approximately 880 mm.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Treatment</th>
<th>Pre-treatment vegetation</th>
<th>Length of record available</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kylie’s Run</td>
<td>135</td>
<td>Control</td>
<td>Pasture</td>
<td>1989 – 1999</td>
<td>N/A</td>
</tr>
</tbody>
</table>

1. Note that while treatment occurred in 1988/89 streamflow measurement commenced in 1989, thus three years of streamflow data have been used as the calibration period.

Glendhu State Forest, New Zealand
Key References: McLean, 2001; Fahey and Jackson, 1997

The Glendhu catchments are located west of Dunedin on the southeastern south island in an area of mid-altitude tussock grassland. The experiment consists of two catchments, a control and a treated catchment. 67% of the treated catchment was converted to Pinus radiata in 1982. Table 3-15 describes the control and the treated catchment for the Glendhu experiment. The area has a mean annual rainfall of 1350 mm.
Table 3-15: Description of the Glendhu catchment experiment

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Treatment</th>
<th>Pre-treatment vegetation</th>
<th>Length of record available Pre-treatment</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>GH1</td>
<td>310</td>
<td>Control</td>
<td>Tussock Grass</td>
<td>1980-1999</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Cathedral Peak, South Africa

Key References: Dye, 1996; Scott and Smith, 1997; Scott *et al.* 2000

The Cathedral Peak catchments are located in the Province of KwaZulu-Natal. Prior to treatment, the catchments in Cathedral Peak were predominately grassland. These catchments were established to test the effect of afforestation with *Pinus Patula* on streamflow. The Cathedral Peak catchments fall within the summer rainfall region, with 85% of the rainfall occurring between October and March. The mean annual rainfall in these catchments is 1400 mm. Table 3-16 describes the Cathedral Peak catchments.

Table 3-16: Description of the Cathedral Peak research catchments

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Treatment</th>
<th>Pre-treatment vegetation</th>
<th>Length of record available Pre-treatment</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPII</td>
<td>190</td>
<td>75% afforestation with <em>P. patula</em></td>
<td>Native Grassland</td>
<td>1949-1952</td>
<td>1953-1981</td>
</tr>
<tr>
<td>CPIII</td>
<td>138.9</td>
<td>86% afforestation with <em>P. patula</em></td>
<td>Native Grassland</td>
<td>1949-1965</td>
<td>1966 – 1980</td>
</tr>
<tr>
<td>CPIV</td>
<td>94.7</td>
<td>Control</td>
<td>Grassland</td>
<td>1949 - 1993</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Jonkershoek, South Africa


The Jonkershoek Valley is located in the Western Cape Province. The climate is Mediterranean type with warm, dry summers and cool wet winters. The mean annual precipitation is 1180 mm. Prior to treatment, the native vegetation was tall open to closed fynbos shrub-land. Five catchments within the Jonkershoek experimental area were planted with *Pinus radiata* to assess the impacts of afforestation on streamflow. Table 3-17 describes the five treated catchments and the control catchment in this experimental group.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Treatments</th>
<th>Pre-treatment vegetation</th>
<th>Length of record available</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bosboukloof</td>
<td>200</td>
<td>57% afforestation with <em>P. radiata</em></td>
<td>tall open to closed fynbos shrub-land</td>
<td>1937 – 1941¹</td>
<td>1942 - 1975</td>
</tr>
<tr>
<td>Biesievlei</td>
<td>27</td>
<td>98% afforestation with <em>P. radiata</em></td>
<td>tall open to closed fynbos shrub-land</td>
<td>1938 - 1948</td>
<td>1949 - 1983</td>
</tr>
<tr>
<td>Tierklook</td>
<td>157</td>
<td>36% afforestation with <em>P. radiata</em></td>
<td>tall open to closed fynbos shrub-land</td>
<td>1938 – 1956</td>
<td>1957 – 1991</td>
</tr>
<tr>
<td>Langrivier</td>
<td>245</td>
<td>Control</td>
<td>tall open to closed fynbos shrub-land</td>
<td>1942 - 1992</td>
<td>N/A</td>
</tr>
</tbody>
</table>

¹ Note Planting of *P. radiata* started in 1937, however, as no streamflow data is available prior to the commencement of planting; the first 4 years have been used as representative of pre-treatment conditions.

Uitsoek State Forest, South Africa

Key References: Van Lill et al. 1980; Dye, 1996; Scott and Lesch; 1997; Scott and Smith; 1997; Scott et al, 2000.

The Mokobulaan experimental catchments in the Uitsoek State Forest were set up to complement the experimental catchments in Jonkershoek and Cathedral Peak. Prior
to treatment, the experimental catchments were predominately grassland. The Mokobulaan area experiences cool dry winters and hot wet summers and has a mean annual rainfall 1180 mm of which 82% falls in the summer months. The aim of the Mokobulaan experimental catchments was to measure the effect of *Eucalyptus grandis* and *Pinus patula* on streamflow. Table 3-18 describes the treatments in the Mokobulaan catchments.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Treatments</th>
<th>Pre-treatment vegetation</th>
<th>Length of record available</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mokobulaan C</td>
<td>36.9</td>
<td>Control</td>
<td>Grassland</td>
<td>1956 - 1999</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Westfalia, South Africa**

Key References: Scott and Smith, 1997; Scott *et al.*, 2000.

The Westfalia paired catchment experiment is located on the slopes of the Great Eastern Escarpment, 13km southwest of Duiwelskloof and has a mean annual rainfall of 1253 mm. In 1938, the vegetation in the catchments is described as grassland, with the riparian zones covered in indigenous bush. Fire was excluded from the catchments and indigenous forest had been established in the catchments by the time the treated catchment was afforested in 1983. Thus, the pre-treatment vegetation in these catchments is mainly mixed scrub forest with closed canopy. Table 3-19 provides details of the control and treated catchments.
Chapter 3: Data Description

Table 3-19: Description of the Westfalia experimental catchments

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Treatments</th>
<th>Pre-treatment vegetation</th>
<th>Length of record available Pre-treatment</th>
<th>Post-treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Westfalia D</td>
<td>39.6</td>
<td>83% afforested with Eucalyptus grandis</td>
<td>mixed scrub forest with closed canopy</td>
<td>1975-1983</td>
<td>1984 - 1998</td>
</tr>
<tr>
<td>Westfalia B</td>
<td>32.6</td>
<td>Control</td>
<td>mixed scrub forest with closed canopy</td>
<td>1975 - 1998</td>
<td>N/S</td>
</tr>
</tbody>
</table>

Plynlimon, United Kingdom


The Plynlimon research catchments are located in mid-Wales. Unlike the majority of other catchments considered in this data set, this pair of catchments do not have a control period during which both catchments are under similar land use. This study provides a comparison between two catchments, one primarily under grass (Wye) and the other 67% forested (Severn). Data were provided for the period 1972 to 1985, during this period the mean annual rainfall was 2500 mm in the Wye catchment and 2487 mm in the Severn catchment. Table 3-20 provides details of the two catchments.

Table 3-20: Description of the Plynlimon experimental catchments

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Vegetation</th>
<th>Length of record available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Severn</td>
<td>1055</td>
<td>67% forested catchment</td>
<td>1971 - 1985</td>
</tr>
<tr>
<td>Wye</td>
<td>870</td>
<td>Grazing/Moorland</td>
<td>1971 - 1985</td>
</tr>
</tbody>
</table>

3.3.5 Other experimental studies

Pine Creek

Key Reference: Linke et al., 1995.

Pine creek is a small experimental catchment located in southeastern Australia. In the late 1980’s, 100% of the catchment was changed from grazing to pine plantation, resulting in significant changes in streamflow. The Pine creek catchment has a mean annual rainfall of 830mm year. As no control catchment is available for this experiment, it has only been used to test the predictive model described in chapters 6 to 7.
3.4 Rainfall Data

All paired catchments had daily rainfall data available as well as daily streamflow. The data have been used as provided by the custodians of the data. All of the data sets used have been previously published and are therefore assumed to be of good quality. To assess the data for anomalies, each data set was also plotted and visually scanned. In addition to this, no anomalies were identified during analysis of the data in Chapters 4, 5 and 6.

3.5 Potential Evapotranspiration Data (PET)

Mean monthly PET data used in Chapters 6 was obtained from the Australian Bureau of Meteorology for the Australian catchments and from the South African Atlas of Agrohydrology and Climatology for the South African catchments. Mean monthly PET data for Glendhu were also obtained to allow this New Zealand catchment to be used in the analysis.

3.6 Conclusion

All the paired catchments studies describe above have been used in the analysis described in Chapters 4 and 5. Only the 17 afforestation and deforestation experiments from Australia, New Zealand and South Africa have been used in development and testing of the FDC adjustment model described in Chapter 6. In addition to the paired catchment studies, the Pine Creek experimental site has also been used in the testing of the model to predict the impact of forest cover changes on the FDC.
CHAPTER 4  Impact of forest cover changes on annual streamflow and flow duration curves.

4.1 Introduction

In predicting the impact of forest cover changes on streamflow it has been shown that predictions of changes to mean annual streamflow are well supported by a range of studies (Zhang et al., 2001) but the predictions of changes to annual, monthly and daily streamflow become progressively more difficult (Vertessy, 1999). This is because on a mean annual basis, climatic variability and storage impacts are effectively removed by averaging streamflow over a long period. This makes it easy to compare the average streamflow between catchments under different amounts of forest cover. The review of Brown et al. (2005) discussed the fact that differences in mean annual streamflow between catchments under different amounts forest covers do not tell the entire story about the impact of forest cover changes on streamflow. This review also highlighted the importance of understanding the impact of forest cover changes on streamflow at shorter time scales, as many catchment management issues require changes to be predicted on annual or sub-annual timescales. Many of these catchment management issues also require information on likely changes in the distribution of flows. Different individual paired catchment studies have shown that different types of responses are observed at the annual and sub-annual time scale for different types of treatments (Scott and Smith, 1997; Watson et al., 1999; Brown et al., 2005). In this chapter the impact of the four different forest cover changes (afforestation, deforestation, forest conversion and forest regrowth) are considered.

The impact of forest cover changes at annual timescales gives us an understanding of the magnitude of the change and the time it takes for the change in streamflow to occur. However, in many instances it is also important to understand how vegetation changes impact on shorter time scales. One of the difficulties in assessing how streamflow at the monthly or daily time step is affected by forest cover is to decide on a method that can summarise the characteristics of the streamflow time series in an easy-to-understand way. The flow duration curve (FDC) provides a good means of summarising a streamflow record that comprises a number of data points, such as daily or monthly streamflow. FDCs are widely used for summarising a streamflow time series in hydrology (Vogel and Fennessey, 1995). However, very few studies assess the impact of forest cover changes on FDCs and none try to compare the results across different catchments in different parts of the world. Studies that have looked at the impact of forest cover changes on the FDC include Burt and Swank (1992), Hickel
Chapter 4: Paired catchment analysis

(2001), McLean (2001), Silberstein et al. (2004), and Lane et al. (2005). As with the comparison of annual flows, the methods used to assess the changes in the FDC differ for each of these individual studies, making it difficult to compare the results across the range of catchments.

To assess the impact of forest cover changes on streamflow at the annual and sub-annual time step it is important that catchment data are analysed using a consistent method (Watson et al., 1999). This allows results to be compared and conclusions to be drawn across the range of catchment studies. Many studies have looked at the impact of forest cover changes on streamflow at the annual time step (Kuczera, 1987; Watson et al., 1999; Scott and Smith, 1997; Hornbeck et al., 1993). However, each of these individual studies used a different method to estimate the change in annual streamflow, making it difficult to draw general conclusions. While the results of these studies all tell us that similar responses are observed for the different types of forest cover change, a consistent method of analysis is needed to ensure comparability of the results.

In this chapter, consistent methods of analysing paired catchment data are used to assess the impact of forest cover change on annual streamflow and FDCs. The annual response and FDC analysis are undertaken to improve our understanding of the types of responses that can be expected following changes in forest cover. This chapter describes the method used to assess annual streamflow response and FDCs. The results of the analysis are then summarised and discussed.

4.2 Data

Data from 46 paired catchment studies have been used in this chapter. These comprise of 12 afforestation experiments (converting from pasture to forest cover), 4 deforestation experiments (clearing and allowing pasture to re-establish or keeping vegetation free), 29 regrowth experiments (clearing with the same tree species being planted or allowed to re-grow) and 1 forest conversion experiment (conversion from native forest to plantation). All of the experimental catchments have been used to assess the annual changes in streamflow, while only the 16 afforestation and deforestation experiments have been used for the FDC analysis. Descriptions of these catchments can be found in Chapter 3. It should be noted that the Plynlimon and Pine Creek catchments have not been used in the analysis in this chapter. This is due to a lack of a calibration period in the Plynlimon catchment, and the lack of a control catchment in the Pine Creek catchment.
4.3 Methodology

4.3.1 Estimating the change in annual streamflow

The methodology outlined in Watson et al. (2001) for analysing paired catchment data has formed the basis for the methodology used to assess the magnitude of annual streamflow changes for all of the paired catchment studies used in this chapter. Watson et al. used log/log regression with an explicit seasonal component to determine the relationship between monthly streamflow in the control and treated catchment during the calibration period. To remove the serial correlation from the residuals a lag-one autoregressive model (AR1) was used to calculate the disturbance. The removal of the serial correlation means that the disturbance is not a measure of the total change in flow during a particular month, however, it allows the statistical significance of change in flow to be determined. In this chapter, the explicit (or deterministic) seasonal component is dropped but the analysis is still performed on monthly data. The inclusion of a seasonal component by Watson et al (2001) implies there is a difference between the control and the treated catchment that varies seasonally in a systematic manner. It was considered that, for most of the paired catchments studies this was not going to be the case, thus, the seasonal component does not add any extra value to the analysis.

Monthly data has been used in this analysis as short pre-treatment periods in most paired catchment studies limit the reliability of the annual regression analyses. The advantage of using monthly data is that there are 12 times as many data points, than in the analysis of annual data. However, it is important to note that while the use of monthly data represents more information and thus makes the regression analysis more reliable, if the monthly serial correlation is significant, it does not represent 12 times the information in the annual data.

To calculate confidence intervals for the monthly change in streamflow, it is important that the following statistical requirements be met. The samples must be uniformly distributed, the residuals must have a constant variance with respect to predicted values (homoscedastic residuals), and the residuals must not be serially correlated, and, must be normally distributed. As shown in Watson et al. the use of a linear regression between monthly flows rarely gives homoscedastic residuals as the variance of the residuals increases as flow increases, thus transformation of the data is required. Watson et al. (2001) adjusted for these heteroscedastic residuals by using a log/log regression. The use of the log/log regression is appropriate in catchments where the data contain no months of zero streamflow. The data set used in this chapter
contains a number of ephemeral streams with months of zero flow data. Thus, a log/log transformation is not appropriate. In order to gain homoscedastic residuals a transformation is required that will accommodate a time series with zero flow values. Using a fifth root has a similar effect to the use of log transformation and has been used in the regression equation relating monthly data (Equation 4-1).

\[
\frac{1}{y^{5}} = \alpha + \beta x^{5} + \epsilon
\]

Equation 4-1

Here \(x\) is the monthly flow in the control catchment, \(y\) is the monthly flow in the treated catchment and \(\alpha\) and \(\beta\) are the coefficients of the regression relationship and \(\epsilon\) is a serially correlated (AR1), zero mean, normally distributed error term.

To calculate 95% confidence intervals and determine the significance of the observed change in streamflow, it is necessary to remove any auto-correlation between the monthly flow results. This has been achieved by assessing the lag-one auto-regressive (AR1) model. Thus, the disturbance \(a_t\) is given by Equation 4-2.

\[
a_t = \epsilon_t - \phi \epsilon_{t-1}
\]

Equation 4-2

Here, \(\phi\) is the auto-regression parameter, estimated as the lag one auto-correlation coefficient.

Once the disturbance, \(a_t\), has been calculated it can be removed and the significance of the monthly residuals can be determined and, hence, it is possible to assess in which months significant changes in streamflow occur. While the calculation of the disturbance allows the statistical significance of the changes in monthly streamflow to be tested, it does not allow the magnitude of the change to be quantified. This requires the re-linearization of the residues (\(\epsilon\)) from the model described in Equation 4-1 for each year. Once the magnitudes of the monthly streamflow changes are determined, the magnitude of the annual results can be calculated.

To minimise the impact of difference in soil water storage at the beginning of each year on the annual results, the annual streamflow is based on water years. In this chapter, the start of the water year is defined as being the first day of the month following the average lowest three-month period of streamflow, which was determined from the average monthly flows in the control catchments. Once the magnitude of the annual...
streamflow changes have been determined the timing of annual changes can be investigated.

4.3.2 Fitting response curves to annual streamflow results

To assess the annual changes in streamflow, only catchments that show a statistically significant change in monthly streamflow are used. This is done to ensure that when the changes are compared across catchments only catchments showing a change due to forest cover are included. Following the estimation of annual flow changes, response curves are fitted to the annual results. For afforestation and deforestation experiments, a response curve was fitted to each data set to establish the time taken for each catchment to reach a new equilibrium. A variation of the sigmoidal curve used by Scott and Smith (1997) and Lane et al. (2005) is adopted in this chapter (Equation 4-3).

\[
\Delta Q = A \left[ \frac{1}{1 + \exp \left( \frac{Age - T}{n} \right)} \right] - 1
\]

Equation 4-3

In Equation 4-3, \( \Delta Q \) is the change in annual streamflow, \( A \) is the change in mean annual streamflow or percentage change in streamflow, \( Age \) is the year after treatment, \( T \) and \( n \) are constants.

This sigmoidal curve is fitted to the annual results for each catchment by maximising the coefficient of efficiency (\( E \)) (Legates and McCabe, 1999), Equation 4-4, for both the absolute change in streamflow and the percentage change in streamflow. This analysis allows the change in annual response over time to be investigated for all afforestation and deforestation experiments.

\[
E = 1 - \frac{\sum_{i=1}^{N} (O_i - P_i)^2}{\sum_{i=1}^{N} (O_i - \bar{O})^2}
\]

Equation 4-4

Here, \( E \) is the coefficient of efficiency, \( O \) is the annual change in streamflow for each year, and \( P \) is the predicted change for each year from Equation 4-3.

In the case of regrowth and forest conversion experiments, a sigmoidal curve is not fitted to the observed changes in streamflow because the shape of the response is
more akin to the Kuczera curves (Kuczera, 1987) or the curves proposed by Watson et al. (1999). A modified version of the expression proposed by Watson et al. has been fitted to the results of each of the regrowth and forest conversion experiments (Equation 4-5). This curve was fitted by maximising the coefficient of efficiency (E). However, unlike the curve proposed by Watson et al. (1999) the parameters are not given any physical meaning.

\[
\Delta Q = a\text{Age} \exp(b\text{Age}) + c\left(\frac{2}{1+\exp(d\text{Age})} + \exp(e\text{Age}) - 2\right)
\]

Equation 4-5

Here \(\Delta Q\) is the change in streamflow, \(\text{Age}\) is the number of years after treatment and \(a, b, c, d\) and \(e\) are all constants.

Equation 4-5 has a significant number of parameters, which raises the possibility that they may be hard to identify. In practice, it was found that all the parameters are identifiable for the data sets used in this thesis. The advantage of the high number of parameters is added flexibility to fit the more complicated response in the regrowth catchments, which outweighed the disadvantage of having a five parameter model.

### 4.3.3 Calculating changes in Flow Duration Curves

One way to evaluate the effect of land use change on a streamflow at shorter time steps is to examine the changes in a catchment’s FDC. In order to assess the changes in a catchment’s FDC following a change in forest cover it is necessary to separate the climate and forest cover impacts on the FDC. The impact of climate on the percentiles of the FDC can be effectively removed by the paired catchment analysis outlined in Burt and Swank (1992). A regression model relating the control and treated catchment is developed for each afforestation and deforestation experiment. The regression model adopted has been selected to give more equal weighting to all flows. As with the monthly analysis the fifth root (Equation 4-6) has been used as it allows the inclusion of zero flow values in the analysis.

\[
\frac{1}{5}Q_{\text{treated}} = \alpha + \beta \frac{1}{5}Q_{\text{control}} + \epsilon
\]

Equation 4-6

Here \(Q_{\text{treated}}\) is the streamflow for the percentiles in the treated catchments and \(Q_{\text{control}}\) is the streamflow for percentiles in the control catchments, \(\alpha\) and \(\beta\) are the recession constants and \(\epsilon\) is the error. In this chapter, the following percentiles are used: 5th, 10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, 90th and 95th. These percentiles are calculated
each water year in the calibration period. Percentiles from all years are then used to develop the relationship between streamflow in the control and treated catchments.

Once the relationship between the streamflow in the control and treated catchment is determined for the calibration period the percentiles that would have occurred had no change in forest cover occurred are estimated for the post treatment period. These predicted percentile flows are then compared to the observed percentile flows in the treated catchment. This allows us to assess the impact of forest cover on different percentiles of the FDC and improves our understanding of how different catchments respond to permanent changes in forest cover.

4.4 Results – Annual Water Yield

4.4.1 Afforestation and deforestation experiments

To allow comparisons to be made between the different experimental catchments, the results need to be adjusted for treated area. For afforestation and deforestation experiments, all results have been adjusted to represent the impact of treating 100% of the catchment area. This is done by linear scaling as shown in Equation 4-7 (Bosch and Hewlett, 1982).

\[
\text{Change}_{100} = \frac{\text{Change}_{\% \text{treated}}}{\% \text{treated}}
\]  

Here, \( \text{Change}_{100} \) is the annual change scaled to represent 100% of the treated area, \( \text{Change}_{\% \text{treated}} \) is the annual change predicted for the area treated. For example, if 80% of the area was treated and the annual reduction was 100 mm, using linear scaling to 100% of the area treated, the annual reduction is 100 divided by 0.8 or 125 mm.

The percentage change in streamflow is calculated by dividing the observed change in streamflow (scaled to 100% of area treated) by the flow that would have occurred in the catchment if there had been no forest cover change. Given that afforestation reduces streamflow, this bounds the percentage change to between 0% and -100%. Dividing the observed flow by the predicted flow removes some of the variations due to wet and dry years that are seen the plots depicting the absolute change in streamflow. These plots are only provided for the afforestation catchments. Due to the direction of change in deforestation experiments, the percentage reduction is not bounded to between 0% and 100%.
Figure 4–1 and Figure 4–2 show a fit of the sigmoidal curves to the observed results for the absolute change in streamflow and for the percentage change in streamflow respectively in the Red Hill catchment. The results show the variation between change in streamflow (Figure 4–1) and percentage change in streamflow (Figure 4–2). Table 4-1 shows the coefficient of efficiency ($E$) for the sigmoidal curve for change in streamflow and the percentage change in streamflow. The results for the percentage changes in streamflow conform to the shape of the sigmoidal curve better than the absolute changes, as highlighted in Figure 4–1 and Figure 4–2. Note that all calibration years plot at year zero on Figure 4–1 and Figure 4–2.

![Figure 4–1](image1)

**Figure 4–1:** Fit of the sigmoidal model to changes in streamflow scaled to 100% of the catchment area treated (Red Hill, Australia). The y axis shows the change in streamflow from the predicted streamflow in the catchment if no change in forest cover had occurred.

![Figure 4–2](image2)

**Figure 4–2:** Fit of the sigmoidal model to the percentage changes in streamflow scaled to 100% of the catchment area treated (Red Hill, Australia).
Table 4-1: Coefficient of efficiency (E) for each sigmoidal curve for all afforestation experiments, indicating that for the majority of catchments the percentage change in streamflow conform to the shape of sigmoidal model better than the absolute change in streamflow.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Change in streamflow</th>
<th>Percentage change in streamflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red Hill</td>
<td>0.30</td>
<td>0.91</td>
</tr>
<tr>
<td>Glendhu</td>
<td>0.92</td>
<td>0.95</td>
</tr>
<tr>
<td>Biesievlei</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Bosboukloof</td>
<td>0.49</td>
<td>0.37</td>
</tr>
<tr>
<td>Cathedral Peak II</td>
<td>0.76</td>
<td>0.85</td>
</tr>
<tr>
<td>Cathedral Peak III</td>
<td>0.89</td>
<td>0.84</td>
</tr>
<tr>
<td>Lambrechtsbos A</td>
<td>0.55</td>
<td>0.46</td>
</tr>
<tr>
<td>Lambrechtsobs B</td>
<td>0.71</td>
<td>0.72</td>
</tr>
<tr>
<td>Mokobulaan A</td>
<td>0.78</td>
<td>0.88</td>
</tr>
<tr>
<td>Mokobulaan B</td>
<td>0.75</td>
<td>0.81</td>
</tr>
<tr>
<td>Tierkloof</td>
<td>0.22</td>
<td>0.26</td>
</tr>
<tr>
<td>Westfalia D</td>
<td>0.70</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Median Coefficient of efficiency 0.73 0.82

Figure 4–3 presents the fitted sigmoidal curves of all afforestation catchments for the percentage change in streamflow. This allows a comparison of the timing of changes in streamflow, among the catchments to be investigated.

Looking at only the catchments with E values greater than 0.5 the timing of responses following afforestation can be grouped into three broad categories. Rapid response catchments, where the change occurs in less than 10 years, medium response catchments, where the change occurs between 10 and 20 years, and slow response catchments, where the change takes more than 20 years to occur. These categories
are used to group the FDC responses described in Section 4.5. From Figure 4–3 it can be seen that the time taken for a catchment to reach a new equilibrium can be divided into three sections. The three sections are, (i) the time it takes for the initial 10 percent of the change to occur, (ii) the time taken for the middle 80% of the change to occur and (iii) the time for the final 10% of the change to occur. These results are summarised for all afforestation catchments in Figure 4–4. The figure shows how the initial 10 percent of the change affects the overall response time. For example, in the Red Hill catchment, the change in streamflow starts immediately following the land use change and proceeds rapidly with the initial 10% of streamflow happening in first 2 years, the main change (the time taken for the middle 80% of the change to occur) takes approximately three years. In contrast, the Biesievlei catchment takes a long time for the change to start occurring, with the initial 10% of the change taking approximately 10 years. The time taken for the middle 80% of the change to occur is similar to Red Hill at approximately 4 years. Of the three rapid response catchments, two were planted with *Eucalypts*, while the other was planted with *Pinus radiata*. The remaining catchments in the sample were planted with either *Pinus radiata* or *Pinus patula*.

![Figure 4–4: Time taken for change in streamflow to occur in afforestation catchments.](image)

As with the afforestation experiments, the annual results from all the deforestation experiments are summarised so the timing of the changes can be assessed. Figure 4–
Chapter 4: Paired catchment analysis

5 shows the annual responses for the four deforestation experiments. For deforestation experiments the change as a percentage of streamflow has not been used to summarise the results as the percentage changes are not bound to 100% change as they are with afforestation experiments. Table 4-2 shows the coefficient of efficiency for each of the deforestation experiments and reveals that in the Don catchment the E value is low (0.28) and therefore will not be considered. Figure 4–6 depicts the time taken for the deforestation catchments to respond to a change in land use. It can be seen that both the Wight and Witklip catchments respond more quickly than the Lemon catchment. This is probably due to the treatment type, with only 54% of the Lemon catchment being cleared compared to 100% in the Wight catchment. The delayed response in the Lemon catchment may be due to the time it takes for the groundwater to respond to change in vegetation (Ruprecht and Schofield, 1989).

![Figure 4–5: Response of all deforestation experiments to age of vegetation, with sigmoidal curve fitted](image)

---

Table 4-2: Coefficient of efficiency for each sigmoidal curve for all deforestation experiments

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Coefficient of efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Don</td>
<td>0.28</td>
</tr>
<tr>
<td>Lemon</td>
<td>0.84</td>
</tr>
<tr>
<td>Wight</td>
<td>0.72</td>
</tr>
<tr>
<td>Witklip</td>
<td>0.51</td>
</tr>
<tr>
<td><strong>Median Coefficient of efficiency</strong></td>
<td><strong>0.62</strong></td>
</tr>
</tbody>
</table>
Figure 4–6: Time taken for the change in streamflow to occur in deforestation experiments. The response time has been divided into three sections, the time for the initial 10% of the change to occur, the time for the middle 80% of the change, and the time for the final 10% change.

4.4.2 Regrowth and forest conversion experiments

Regrowth and forest conversion experiments make up the majority of the catchments analysed in this chapter. Regrowth and forest conversion studies are limited in their usefulness when assessing the impact of permanent changes in forest cover because the hydrology generally does not reach a new (non-forested) equilibrium before forested conditions are re-established. However, in many environments it is likely that changes in forest age structure will affect streamflow. Therefore, regrowth and forest conversion experiments have been used to assess the response of forested catchments to changes in age structure. Results have only been presented for catchments with at least 30% change in forest cover. Those with less than 30% change in cover did not exhibit a significant change in monthly streamflow following change in vegetation. This reduced the number of catchments from 30 to 23.

As described in the methodology, a curve of a shape similar to the one used by Watson et al. (1999) was fitted to the changes in annual water yield observed in the regrowth catchments. Figure 4–7 and Figure 4–8 show the typical fits of the response curves to observed regrowth experiments for a good fit and poor fit respectively.
A curve was fitted to each of the regrowth and forest conversion paired catchment studies, and the coefficient of efficiency was calculated. Where the coefficient of efficiency is less than zero, it indicates that the mean provides a better fit than the response curve. The coefficient of efficiency for each study is shown in Table 4-3.
Table 4-3: Coefficient of efficiency (E) for all regrowth and forest conversion experiments.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Coefficient of efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Spur 1</td>
<td>0.50</td>
</tr>
<tr>
<td>Black Spur 2</td>
<td>0.51</td>
</tr>
<tr>
<td>Black Spur 3</td>
<td>-0.02</td>
</tr>
<tr>
<td>Ettercon 1</td>
<td>0.40</td>
</tr>
<tr>
<td>Ettercon 4</td>
<td>0.53</td>
</tr>
<tr>
<td>Monda 1</td>
<td>0.09</td>
</tr>
<tr>
<td>Monda 2</td>
<td>0.14</td>
</tr>
<tr>
<td>Monda 3</td>
<td>0.76</td>
</tr>
<tr>
<td>Myrtle 2</td>
<td>0.78</td>
</tr>
<tr>
<td>Blue Jacket</td>
<td>0.87</td>
</tr>
<tr>
<td>Picaninny</td>
<td>0.75</td>
</tr>
<tr>
<td>Wicksend</td>
<td>0.92</td>
</tr>
<tr>
<td>Willbob</td>
<td>0.93</td>
</tr>
<tr>
<td>Geebung Creek</td>
<td>0.32</td>
</tr>
<tr>
<td>Germans Creek</td>
<td>0.81</td>
</tr>
<tr>
<td>Stringybark Creek</td>
<td>0.77</td>
</tr>
<tr>
<td>HJ Andrews 1</td>
<td>0.76</td>
</tr>
<tr>
<td>HJ Andrews 6</td>
<td>0.14</td>
</tr>
<tr>
<td>HJ Andrews 7</td>
<td>0.46</td>
</tr>
<tr>
<td>HJ Andrews 10</td>
<td>-0.04</td>
</tr>
<tr>
<td>Coyote 1</td>
<td>0.46</td>
</tr>
<tr>
<td>Coyote 3</td>
<td>0.48</td>
</tr>
<tr>
<td>Stewarts Creek</td>
<td>0.80</td>
</tr>
<tr>
<td><strong>Median Coefficient of efficiency</strong></td>
<td><strong>0.49</strong> *</td>
</tr>
</tbody>
</table>

\* indicates forest conversion experiment

Figure 4–9 shows the response of regrowth experiments and forest conversion experiments to age of vegetation for all catchments with coefficients of efficiency greater than 0.5. This figure shows that for most regrowth experiments, there is an initial increase in streamflow, followed by a decrease. The maximum increase generally occurs during the first 5 years after treatment. The time it takes for catchments to return to pre-treatment conditions depends on the time over which the treatment occurs and the age of the initial vegetation, as shown in Figure 4.9 most catchments do not return to pre-treatment conditions within the length of the available data. Where a reduction in flow occurs, this is most likely to be due to the rapid regrowth that have a greater rate of transpiration than old growth vegetation as shown by Kuczera (1987).
The results of the regrowth experiments and forest conversion experiments show that, in general, the increase in streamflow in regrowth catchments lasts for between 3 and 10 years, with the peak increase occurring during the first 6 years.

4.4.3 Response times for all experimental types

The above sections have focused on the different experimental types and the time it takes for catchments to respond to both permanent and temporary changes in forest cover. It shows that changes in streamflow because of afforestation and deforestation are expected to plateau to a new equilibrium, while for regrowth and forest conversion experiments, the change is more dynamic. In general, there is an initial increase in flow. This is followed by either a return to pre-treatment flows or a decrease in streamflow to below pre-treatment conditions followed by a final increase back to pre-treatment flows. These changes occur over a timescale that can be many decades. Based on the catchment data analysed, Figure 4–10 provides a comparison of the annual response in afforestation, deforestation, regrowth and forest conversion experiments. This figure shows the difference between afforestation and deforestation experiments. It can be seen that the afforestation catchments adjust more slowly than catchments subjected to other treatment types. This is understandable as with afforestation there is a period before the trees establish and influence the hydrology of the catchment. It also shows that while there is a rapid increase in streamflow in
regrowth experiments, this increase has, in general, subsided before the deforestation experiments has reach a new equilibrium. This indicates that regrowth and forest conversion experiments cannot easily be used to investigate the impact of permanent change in forest cover.

![Figure 4-10: Timing of streamflow changes for different types of treatment.](image)

**4.5 Results - Flow Duration Curves**

This section describes a comparison between the observed FDCs and those predicted from the calibration relationships (Equation 4-5) for afforestation and deforestation experiments. Table 4-4 provides the regression parameters \((a\) and \(b\)) and \(R^2\) for each catchment analysed. Forest conversion and regrowth experiments have not been included as the changes in streamflow are not permanent in nature, thus making the choice of period over which to estimate the FDCs difficult. FDCs are presented as both linear and log plots. The linear plots allow the changes in high flows to be assessed while the log plots allow the impacts on low flows to be investigated. Two sets of curves are shown – the observed curve and those predicted using Equation 4-5 (i.e. the control or “no change” FDCs). Comparing the two in the post-treatment equilibrium period for each catchment allows an assessment of the change in FDC due to the experimental treatment. The afforestation catchments have been grouped based on the response times identified in Section 4.4.1. This is done to assess the similarities in FDC response for catchments with similar annual response times. The afforestation
catchments that showed poor fits for the sigmoidal curve in Section 4.4.1, have been grouped together as a fourth data set.

<table>
<thead>
<tr>
<th>Table 4-4: Regression parameters and $R^2$ from Equation 4-5 for each afforestation and deforestation study.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment</td>
</tr>
<tr>
<td>Red Hill</td>
</tr>
<tr>
<td>Glendhu</td>
</tr>
<tr>
<td>Biesievel</td>
</tr>
<tr>
<td>Bosboukloof</td>
</tr>
<tr>
<td>Cathedral Peak II</td>
</tr>
<tr>
<td>Cathedral Peak III</td>
</tr>
<tr>
<td>Lambrechtsbos A</td>
</tr>
<tr>
<td>Lambrechtsobs B</td>
</tr>
<tr>
<td>Mokobulaan A</td>
</tr>
<tr>
<td>Mokobulaan B</td>
</tr>
<tr>
<td>Tierkloof</td>
</tr>
<tr>
<td>Westfalia D</td>
</tr>
<tr>
<td>Don</td>
</tr>
<tr>
<td>Lemon</td>
</tr>
<tr>
<td>Wight</td>
</tr>
<tr>
<td>Witklop</td>
</tr>
</tbody>
</table>

Figure 4–11 presents the FDCs for the rapid response afforestation catchments (Red Hill, Mokobulaan A and Westfalia D). These catchments show the most marked reductions in streamflow. Two of the catchments, Westfalia D and Mokobulaan A, stop flowing 100% of the time, while Red Hill showed a substantial reduction in the percentage of time flow occurs. The results in the upper right hand corner of Figure 4–11 show the main volume reduction for Red Hill occurs in the high flow section of the curve, while there is a proportionally larger reduction in the low flow section of the FDC. As Westfalia D and Mokobulaan A stop flowing completely there is 100% reduction in all flows for these catchments in the year depicted.
Chapter 4: Paired catchment analysis

Figure 4–11: Flow duration curves for the rapid response catchments. Plots on the left (A and B) show the first year of the calibration period, plots on the right (C and D) show the FDC following land use change. The flows in the lower figures (B and D) are plotted on a log scale. The predicted FDCs show the FDCs that would be expected if no change in land use had occurred. It should be noted at on Figure D the observed FDCs for Mokobulaan A and Westfalia D do not appear, as there was no flow in these catchments during the year plotted.

Figure 4–12 shows the FDCs for the medium response time catchments, three of the four catchments in this group remain perennial following treatment, while the fourth catchment, Mokobulaan B, exhibits a reduction in the percentage of time flow occurs. Again, these catchments show that the major volume reduction occurs in the high flows. Two of the catchments (Mokobulaan B and Lambrechtsobs B) have larger percentage reduction in the lower flows. The remaining catchments have a more uniform percentage reduction across all flow percentiles.
Chapter 4: Paired catchment analysis

Figure 4–12: Flow duration curves for the medium response catchments. Plots on the left (A and B) show the first year of the calibration period, plots on the right (C and D) show the FDC following land use change. The flows in the lower figures (B and D) are plotted on a log scale. The predicted FDCs show the FDCs that would be expected if no change in land use had occurred.

The slow response catchments (Figure 4–13) remain perennial following afforestation, with the major volume reduction occurring in the higher flows (or lower percentiles). There is a larger percentage reduction in the lower flows in both these catchments. The three catchments with poor fits for the annual response curves are shown in Figure 4–14. The catchments all remain perennial following the change in forest cover and show a more a uniform reduction in streamflow across the complete range of flows.
Chapter 4: Paired catchment analysis

Figure 4–13: Flow duration curves for the slow response catchments. Plots on the left (A and B) show the first year of the calibration period, plots on the right (C and D) show the FDC following land use change. The flows in the lower figures (B and D) are plotted on a log scale. The predicted FDCs show the FDCs that would be expected if no change in land use had occurred.
Chapter 4: Paired catchment analysis

Figure 4–14: Flow duration curves for remaining afforestation catchments. Plots on the left (A and B) show the first year of the calibration period, plots on the right (C and D) show the FDC following land use change. The flows in the lower figures (B and D) are plotted on a log scale. The predicted FDCs show the FDCs that would be expected if no change in land use had occurred.

Figure 4–15 and Figure 4–16 show the percentage and volume reductions in streamflow for the afforestation experiments. The percentage reductions show that the majority of catchments have larger proportional reductions in lower flows (or higher percentiles). However, it is also possible for the larger percentage reductions to occur in the high flows. This response is obvious in the Glendhu and Tierkloof catchments. The volume reductions (Figure 4–16) show that the largest volume reductions occur in the high flows and gradually decrease as the flow decreases.
The deforestation experiments (Figure 4–17) show similar results to the afforestation experiments, but in reverse, (i.e. there is an increase in streamflow compared to a decrease). Three of the catchments in the Collie river basin were ephemeral under forested conditions. When the catchments were cleared, two of these catchments become perennial, while the third shows an increase in the percentage of time flow
occurs in the catchment. The fourth deforestation catchment is perennial prior to treatment and continues to be perennial following the change in forest cover. In all three of these catchments, the major volume change occurs in the higher flows, while there is a proportionally larger increase in the lower flows.

Figure 4–17: Flow duration curves for the deforestation experiments. Plots on the left show the first year of the calibration period, plots on the right show the FDC following land use change. The flows in the lower figures (B and D) are plotted on a log scale. The predicted FDCs show the FDCs that would be expected if no change in land use had occurred.

The results of both the afforestation and deforestation experiments show that FDCs can respond in different ways to changes in forest cover. In all cases, the major volume change occurs in the higher flows, or the flows that occur less often.
4.6 Discussion

4.6.1 Timing of streamflow response

The assessment of the timing of streamflow changes in the different types of paired catchment studies revealed that the time taken for streamflow to respond following permanent changes in forest cover varies considerably. The afforestation catchments could be grouped into three distinct categories based on the response time. The three rapid response catchments, Red Hill, Mokobulaan A and Westfalia D all have years with below average rainfall during the period following treatment. In these catchments the soil water storage becomes depleted more rapidly than would have occurred if average or above average rainfall occurred during this period. Another feature of two of the rapid response catchments is that both Mokobulaan A and Westfalia D, located in South Africa, were planted with eucalypts. However, the Red Hill catchment in Australia was planted with pines.

The four medium response catchments, Glendhu, Lambrechtsbos B, Cathedral Peak III and Mokobulaan B were all planted with either Pinus radiata or Pinus patula. In these catchments, there were no years with significantly below average rainfall in the years following treatment. This may account for the slower response compared to the rapid response catchments. The other feature of the results from these catchments is the time taken for the majority of the reduction in streamflow to occur (the middle 80% of change in Figure 4–4). In three of the catchments (Lambrechtsbos B, Cathedral Peak III and Mokobulaan B), the time for the reduction to occur is longer than in both the rapid and slow response catchments. This could be due to disturbances that occurred during the post treatment period. For example, both the Lambrechtsbos B and Cathedral Peak III catchments underwent thinning and this may have slowed the response (Scott et al., 2000). The medium response catchments show a combination of catchments with winter and summer rainfall dominance. These results may represent the typical length to response in catchments undergoing afforestation. However, additional catchment experiments would be required to confirm these observations.

The two slow response catchments showed that once the change in streamflow begins the time taken for the majority of the change to occur happens over a period similar to the rapid response catchments (Figure 4–4). For the Cathedral Peak II catchment the delay in the time that it takes for the initial 10% of the change to occur can be explained by 15 years over which afforestation occurred (Scott et al. 2000). It would be anticipated that this would delay the response time compared to catchments where the
change in forest cover occurs in a single year. The reasons for the slower response in Biesievlei catchment is less clear. However, it could be that sub-optimal growth conditions (Scott and Smith, 1997) slowed the growth of the plantations in this catchment.

The deforestation experiments show marked differences in the time taken to respond. The catchments in the Collie river basin (i.e. Don, Lemon and Wight) exhibit different timing of the changes in streamflow. In the Don catchment, the magnitude of the change was much smaller than that in the Lemon catchment, despite both catchments having similar rainfall and treated area. These differences can be explained by the different location of the treatment within the catchments. In the Don catchment, the change in vegetation was evenly spread across the catchment, while the clearing in the Lemon catchment occurred in the lower section of the catchment (Silberstein et al., 2004). The clearing of the lower section of the catchment means that the groundwater response is greater in the Lemon catchment. The difference in the responses is also illustrated by the changes in the FDCs, with the Lemon catchment showing a much larger change in all flow percentiles. The differences in the response time between the Lemon and Wight catchments are explained by the mean annual rainfall difference mean annual rainfall in the Wight catchment being 1200 mm/year compared to 750 mm/year in the Lemon catchment. The fourth deforestation catchment, Witklip 6, showed a similar response time to the Wight catchment.

The results of the regrowth and forest conversion experiments can be used to assess the impact of forest age on streamflow. In catchments where forest replaces forest, the annual response is not about establishing when a new equilibrium is reached, but is about trying to establish when the catchment returns to its original flow levels and the shape of the intervening response curve. In the regrowth experiments, there is insufficient data to show when the catchments return to original flow levels. However, the results shown in Figure 4–9 do reveal some interesting characteristics of the response to forest cover change in regrowth and forest conversion experiments. All of the regrowth experiments show an initial increase in streamflow. This increase reaches a maximum anywhere between one and six years (Figure 4–9) the length of time that the increase persists depends on the catchment characteristics and how long the catchment remains clear prior to the regrowth being established. In a number of the catchments the increases in streamflow persists for the period longer than the length of record. The other interesting feature of the regrowth experiments is the time it takes for a reduction in streamflow to occur. In a number of regrowth experiments, it
has been shown that the rapidly growing regrowth uses more water than old growth forests (Watson et al., 1999; Kuczera, 1987; Lane and Mackay, 2001; Cornish and Vertessy, 2001). This finding is supported in a number of the catchments presented here, with Figure 4–9 showing that it takes between three and ten years for a reduction in streamflow to commence.

One of the original intentions of analysing the regrowth experiments was to compare the results to afforestation and deforestation catchments. This was to establish if regrowth experiments could be used to assess how permanent changes in vegetation may affect streamflow. Figure 4–10 showed how the afforestation, deforestation and regrowth catchments compared to each other. These results showed that while regrowth experiments have an initial increase in streamflow, it is less persistent than the deforestation experiments. Figure 4–10 also illustrates the problem with comparing the magnitude of the changes between different treatment types and different catchments. The majority of the regrowth catchments have higher rainfall than the deforestation experiments, and thus have larger increase in streamflow. The initial increase in streamflow in the regrowth experiments would be expected to be less than the long-term equilibrium if a permanent change in land use had occurred. The increase in regrowth is primarily due to decreases in interception following the clearing of vegetation, while the sustained increase in deforestation experiments is due to both changes in the soil water storage and decreases in canopy interception. Figure 4–10 showed that it is not possible to compare the results of regrowth and afforestation experiments. The decreases in streamflow from regrowth catchments are less than the afforestation catchments. This is not surprising, as the initial catchment vegetation in the regrowth catchments will have less streamflow than grass/pastured conditions of the afforestation catchments.

4.6.2 Flow duration curves

The analysis of the flow duration curves for afforestation and deforestation experiments show some interesting patterns, with three distinct response types identified. The four Australian catchments, Red Hill (Figure 4–11), Don, Lemon and Wight (Figure 4–17), illustrate the first type of response where there is a substantial change in the percentage of time flow occurs. All these catchments show more zero flow days under forested conditions than under grass conditions. These catchments all have Mediterranean climate, with wet winters and dry summers. While the rainfall in Red Hill is uniform compared to the Collie river catchments, the increased evapotranspiration in these catchments during the summer months when under forested conditions result in
a larger impact on low flows than high flows. The three other catchments that show a substantial change in the percentage of time flow occurs are all summer dominant rainfall catchments. In these catchments the substantial change in flow may be due to the summer evapotranspiration exceeding the rainfall under forested conditions. This may result in the soil water stores not being replenished by the summer rains and thus, causing flow to cease even during the winter months.

A second group are catchments that all remain perennial following treatment but have a proportionally larger decrease in the low flows compared to the high flows. This response is less extreme than the first group, but is probably controlled by similar processes. In these catchments, it is possible that streamflow is more consistent due to larger soil moisture stores that drain less rapidly, thus allowing streamflow to be more persistent. The third response group has a uniform reduction across all flow percentiles (i.e. Glendhu). This is most likely due to the uniform rainfall throughout the year. The results of the FDC analysis presented here are consistent with those presented in Lane et al. (2005) in which a model that had a climate and vegetation term was used to separate the impact of climate from vegetation on the FDC. This allowed catchments that were not paired to be included in the analyses.

The results of the FDC analysis also showed that while the low flows are proportionally more affected than the high flows, the major volume changes occur in flows that occur less often (that is flows that occur less than 20% of the time). This is expected, as high flows will be affected by both changes in interception and changes in transpiration, while low flow will only be affected by changes in transpiration. Forested catchments are likely to have greater rates of interception rates then grass catchments, thus having lower flows following rainfall events (high flows). This is important to note from a catchment management perspective. If land use in a catchment is being managed for total water yield (for example, a catchment upstream of a water supply reservoir) then the changes in the upper section of the FDC are important. If low flow reliability is important, for run of the river water supply or environmental flows, then the lower flows may be of greater importance. The impact of vegetation on large flood events was not investigated and would required flood analysis to be undertaken, which is outside the scope of this thesis.

4.7 Conclusions

This chapter provided a consistent analysis of paired catchment data with the aim of investigating the timing of water yield changes and changes in FDCs following
permanent changes in forest cover. The results of the annual analysis illustrated the different response seen in afforestation, deforestation and regrowth experiments. These results provide an indication of the time it takes for a catchment to reach a new equilibrium following a permanent change in forest cover. The results of the regrowth experiments indicated that it is not possible to use these studies to evaluate how permanent change in land use impacts on streamflow. However, they do provide us with a contrast to the afforestation and deforestation experiments.

Analysis of the FDCs in the afforestation experiments showed that three types of responses are observed. These are catchments that have a change in the percentage of time flow occurs or in some cases cease to flow all together, catchments that have a proportionally larger reduction in low flows compared to high flow, and catchments that have a uniform reduction in all flows.
CHAPTER 5 Parameterisation of the flow duration curve

Chapter 4 showed how FDCs are affected by changes in forest cover. This analysis allowed us to understand some of the responses we need to consider in developing a predictive model for adjusting the FDC for a permanent change in forest cover. The first step in developing a predictive model is to develop a model for describing shape of any FDC. This model needs to capture the key features of the FDC and allow the parameterisation to be linked to an estimated change in mean annual streamflow. This chapter compares three different parameterisations of the FDC and investigates how the parameters change following alterations to forest cover.


5.1 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).

* The co-authors of this paper were my supervisors and provided guidance in the research
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 chapter 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 chapter 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 chapter 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.

5.2 Methodology and data

5.2.1 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 5–1 depicts the three models considered for defining the FDC. Detailed descriptions of each of the models can be found in Equation 5-1, Equation 5-2 and Equation 5-3.

Model 1 involves the fitting of a single linear curve to the NFDC, this results in a 3 parameter model as described in Equation 5-1. 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 Equation 5-2. Model 3, a five parameter model, involves
fitting an exponential curve to the upper and lower sections of the NFDC, as described in Equation 5-3.

\[
\hat{y} = \begin{cases} 
    Q_{50} \left(10^{a F^{-1}(\frac{x}{CTF})}\right) & x < CTF \\
    0 & x \geq CTF
\end{cases} \quad \text{Equation 5-1}
\]

\[
\hat{y} = \begin{cases} 
    Q_{50} \left(10^{b_1 F^{-1}(\frac{x}{CTF})}\right) & x \leq \frac{CTF}{2} \\
    0 & x \geq CTF
\end{cases} \quad \text{Equation 5-2}
\]

\[
\hat{y} = \begin{cases} 
    Q_{50} \left(10^{b_2 F^{-1}(\frac{x}{CTF})}\right) & \frac{CTF}{2} \leq x < CTF \\
    0 & x \geq CTF
\end{cases} \quad \text{Equation 5-3}
\]

Here \( \hat{y} \) is the predicted flow, \( F^{-1} \) is the inverse of the standard normal cumulative distribution, \( Q_{50} \) is the median of the non-zero flow days, \( CTF \) is the cease to flow percentile (expressed as a percentage), \( x \) is a probability value (0.01-99.99%) and \( a, b_1, b_2, s, c_u, \) and \( c_l \) 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 5.2.3. 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 nonzero flow days to the total number of days. In the determination of the zero flow days it was assumed that any daily streamflow 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 always intersect the axis at the origin.

![Figure 5–1: 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.](image)

To assess how well each of the models reproduced the FDC two criteria were used to determine the model performance. The first criterion was, mass balance, 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 in Equation 5-4.
Chapter 5: Parameterisation of the flow duration curve

\[ E = 1 - \frac{\sum_{i=1}^{N} (O_i - P_i)^2}{\sum_{i=1}^{N} (O_i - \bar{O})^2} \]  
Equation 5-4

here \( O \) is the observed percentile, \( P \) is the predicted percentile and \( N \) is the number of percentiles, 100 in this analysis.

5.2.2 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 5-1.

5.2.3 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 both the period of record and the treatment undertaken. Table 5-2 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 because 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.

† Detailed description of each of the experimental catchments can be found in Chapter 3 of this thesis.
Table 5-1: Summary of experimental catchment groups (Details and key references can be found in Best et al., 2003a).

<table>
<thead>
<tr>
<th>Experimental catchment group</th>
<th>Number of Treated Catchments (number of control catchments)</th>
<th>Treatment Type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>South African</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cathedral Peak</td>
<td>2 (1)</td>
<td>A</td>
</tr>
<tr>
<td>Jonkershoek</td>
<td>5 (1)</td>
<td>A,D</td>
</tr>
<tr>
<td>Mokobulaan</td>
<td>2 (1)</td>
<td>A</td>
</tr>
<tr>
<td>Westfalia</td>
<td>1 (1)</td>
<td>A</td>
</tr>
<tr>
<td>Witklip</td>
<td>1 (1)</td>
<td>D</td>
</tr>
<tr>
<td><strong>United Kingdom</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plynlimon</td>
<td>1 (1)</td>
<td>A</td>
</tr>
<tr>
<td>New Zealand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glendhu</td>
<td>1 (1)</td>
<td>A</td>
</tr>
<tr>
<td><strong>USA</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H.J. Andrews</td>
<td>7 (3)</td>
<td>R</td>
</tr>
<tr>
<td>Coyote Creek</td>
<td>3 (1)</td>
<td>R</td>
</tr>
<tr>
<td>Fox Creek</td>
<td>2 (1)</td>
<td>R</td>
</tr>
<tr>
<td><strong>Australia</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collie Basin</td>
<td>3 (1)</td>
<td>D</td>
</tr>
<tr>
<td>Melbourne Water Catchments</td>
<td>12 (5)</td>
<td>R</td>
</tr>
<tr>
<td>Red Hill</td>
<td>1 (1)</td>
<td>A</td>
</tr>
<tr>
<td>Stewarts Creek</td>
<td>1 (1)</td>
<td>FC</td>
</tr>
<tr>
<td>Tantawangalo</td>
<td>2 (1)</td>
<td>R</td>
</tr>
<tr>
<td>Yambula</td>
<td>3 (1)</td>
<td>R</td>
</tr>
</tbody>
</table>

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

Table 5-2: Period of record used to test for trends in change in water yield.

<table>
<thead>
<tr>
<th>Type of Treatment</th>
<th>Type of Test used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Afforestation</td>
<td>Mann-Kendall from beginning of record to either end of record or clear felling of catchment</td>
</tr>
<tr>
<td>Deforestation</td>
<td>Mann-Kendall from beginning of record to end of record or replanting in the catchment.</td>
</tr>
<tr>
<td>Regrowth</td>
<td>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.</td>
</tr>
<tr>
<td>Forest Conversion</td>
<td>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.</td>
</tr>
</tbody>
</table>
5.3 Results

5.3.1 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 5–2 depicts box plots for each of the model showing the ratio of the predicted to the observed volume, for the Jonkershoek catchment group. Figure 5–3 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 5–2: 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.](image)
The second measure used was the ability of the model to replicate the percentile values on the FDC. The coefficient of efficiency, (Equation 5-4), for each of the FDC was calculated, these results are presented in Table 5-3. Figure 5–4 shows the typical spread in residuals (observed – predicted) for each of the model types for the Jonkershoek catchments in South Africa. Figure 5–4 shows that Model 1 gives a poor model fit for the extreme percentiles. This is supported by the coefficient of efficiency in Table 5-3, where Model 3 has an average coefficient of efficiency of 0.95, compared to 0.61 for Model 1.
Table 5-3: Average coefficient of efficiency for each catchment group.

<table>
<thead>
<tr>
<th>Catchment Group</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathedral Peak</td>
<td>0.86</td>
<td>0.85</td>
<td>0.97</td>
</tr>
<tr>
<td>Jonkershoek</td>
<td>0.83</td>
<td>0.95</td>
<td>0.98</td>
</tr>
<tr>
<td>Mokobulaan</td>
<td>0.59</td>
<td>0.92</td>
<td>0.91</td>
</tr>
<tr>
<td>Westfalia</td>
<td>0.79</td>
<td>0.93</td>
<td>0.97</td>
</tr>
<tr>
<td>Witklop</td>
<td>0.82</td>
<td>0.88</td>
<td>0.97</td>
</tr>
<tr>
<td>Plynlimon</td>
<td>0.71</td>
<td>0.92</td>
<td>0.97</td>
</tr>
<tr>
<td>Glendhlu</td>
<td>0.65</td>
<td>0.89</td>
<td>0.97</td>
</tr>
<tr>
<td>H.J. Andrews</td>
<td>0.10</td>
<td>0.90</td>
<td>0.91</td>
</tr>
<tr>
<td>Coyote Creek</td>
<td>0.62</td>
<td>0.80</td>
<td>0.96</td>
</tr>
<tr>
<td>Fox Creek</td>
<td>0.27</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td>Collie Basin</td>
<td>0.50</td>
<td>0.86</td>
<td>0.97</td>
</tr>
<tr>
<td>Melbourne Water Catchments</td>
<td>0.79</td>
<td>0.94</td>
<td>0.96</td>
</tr>
<tr>
<td>Red Hill</td>
<td>0.56</td>
<td>0.90</td>
<td>0.95</td>
</tr>
<tr>
<td>Stewarts Creek</td>
<td>0.46</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>Tantawangalo</td>
<td>0.81</td>
<td>0.83</td>
<td>0.97</td>
</tr>
<tr>
<td>Yambula</td>
<td>0.78</td>
<td>0.87</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Average Coefficient of Efficiency 0.61 0.90 0.95

5.3.2 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 5-4 shows a summary of the results 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 a deforestation experiment. Figure 5-5 provides a comparison of the fitted parameters for the afforestation control catchments, while Figure 5-6 depicts the correlation between the fitted parameters.

Table 5-4: 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.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Median CTF</th>
<th>Treatment</th>
<th>Median CTF</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF (13)</td>
<td>↑↑↑↑↑↑↑↑↑↑</td>
<td>DF (5)</td>
<td>↓↑↑↑↑↑↑↑↑↑</td>
</tr>
<tr>
<td></td>
<td>↑↑↑↑↑↑↑↑↑↑</td>
<td>RG (13)</td>
<td>↑↑↑↑↑↑↑↑↑↑</td>
</tr>
<tr>
<td></td>
<td>↑↑↑↑↑↑↑↑↑↑</td>
<td>RG (16)</td>
<td>↑↑↑↑↑↑↑↑↑↑</td>
</tr>
<tr>
<td></td>
<td>↑↑↑↑↑↑↑↑↑↑</td>
<td>FC (1)</td>
<td>↑↑↑↑↑↑↑↑↑↑</td>
</tr>
</tbody>
</table>

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. ↑↑ Trend in data from start of record to 5 years post treatment. ↑↑↑↑↑↑↑↑↑↑ Trend in data from first year post treatment to end of record.

![Figure 5-5: Comparison of fitted parameters (s, c_u, c_l) values for the afforestation control catchments. The thick line represents the median, the box the 25th and 75th percentile and the whiskers the range of the parameters for the annual FDCs in each control catchment.](image_url)
Figure 5-6: Correlation between fitted annual FDC parameters for all afforestation experimental catchments (both treated and control catchments). Figure 5-6A shows the relationship between the slope and upper exponent, Figure 5-6B shows the correlation between the slope and lower exponent, Figure 5-6C shows the correlation between the upper and lower exponents.
5.4 Discussion

The results presented in Table 5-3 and Figure 5–3 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 5-4 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 afforestation and deforestation experiments have statistically significant changes for the conditional median and the CTF percentile. The direction of these change are consistent with our understanding of the changes in the streamflow, with afforestation catchment showing a decrease in the conditional median and CTF percentile, while the deforestation experiments show an increase in these parameters. The results of the regrowth experiments show very few catchments showing statistically significant changes in the FDC parameters. This result is no unsurprising as the nature of the regrowth experiments means there streamflow does not have a persistent change in one direction, with an initial increase following a reduction in cover, followed by a return towards pre-treatment conditions as the vegetation re-establishes. These results are consistent with the conclusion drawn from the literature review in Chapter 2 that concluded that regrowth experiments could not be used to predict the impact of permanent vegetation changes.

Figure 5-5 provides a comparison between the parameter values for s, c_u, and c_l for the control catchments for the afforestation experiments. This figure allows a comparison to be made across the different afforestation catchment groups. This figure shows that the range of the fitted parameters is similar for each catchment group. Fitting the model to each annual FDC has allowed the range of parameter values for each
catchment group to be assessed, this range reflects the impact that climate has on the shape of the FDC and thus the fitted parameters.

To assess the robustness of the fitted parameters, the correlation between the parameters was investigated. Figure 5-6 shows plots of the fitted parameters for all afforestation experiments (both the control and treated catchments). Figure 5-6A shows that there is a reasonably strong correlation between the upper exponent and the slope with an $R^2$ value of 0.7. Figures 5-6B and 5-6C indicate that there is little or no correlation between the slope and the lower exponent and upper and lower exponents. This indicates that adjusting the lower exponents should not impact on either the upper exponent or the slope. However, if the slope or upper exponent were to be adjusted for land use change, the other parameter would also need to be adjusted due to the correlation between the two parameters. As Table 5-4 shows no consistent change in either the upper exponent or the slope, these fitted parameters will not be altered during the methodology to adjust the FDC for a change in forest cover outlined in Chapter 6.

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 that 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 an indication of intermittent and perennial streams, with catchments with a baseflow index less than 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, $s$, $c_u$ and $c_l$ parameters relate to different sections of the FDC, $s$ being the slope at the origin of the NFDC and $c_u$ and $c_l$
being the exponents for the upper and lower percentiles respectively. 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 an 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 $c_l$ parameter would be altered as a result in changes to the low flow conditions. The slope parameter ($s$) 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 ($c_u$) is primarily going to be linked to rainfall and rainfall intensity, while the lower exponent ($c_l$) will relate to geology and the CTF point.

5.5 Conclusions

This chapter 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 chapter has the potential to be used for prediction of the FDC in ungauged catchments provided the parameters can be correlated to catchment characteristics.
CHAPTER 6  Adjusting flow duration curves for changes in forest cover

6.1 Introduction

Chapter 5 outlined three possible models to parameterise a catchment’s FDC. The parameters were then investigated to assess how they respond to a change in forest cover. In this chapter, the five-parameter model described in Chapter 5 is adopted as the preferred parameterisation of the FDC. The model is linked to a predicted change in mean annual streamflow to allow the FDC to be adjusted for a change in forest cover. The mean annual flow model developed by Zhang et al. (2001) to predict the impact of forest cover changes on mean annual streamflow has been shown to be robust and has been used to assess the impact of vegetation changes at a regional scale (Zhang et al., 2003). While changes in mean annual streamflow associated with afforestation are important, it is more significant to predict the effects of afforestation on streamflow at shorter time scales. This is because models for water allocation, water quality, and environmental flows all require the ability to predict how monthly or daily flow time series will be affected by changing land use. For example, water allocation models such as the Integrated Quantity and Quality Model (IQQM) (Simons et al., 1996) and Resource Allocation Model (REALM) (Diment, 1991) use daily or monthly catchment inflow data.

Unfortunately, our understanding of the seasonal impact of forest cover change on streamflow is limited and there have been no effective tools available for predicting changes at shorter time scales that are applicable with typical levels of data availability. It is generally understood that afforestation affects not only rainfall interception, which directly influences surface runoff, but also deep drainage (Zhang et al., 1999). The impact on drainage determines the amount of baseflow in a catchment. However, it is difficult to quantify these changes where no detailed experimental data are available. The degree of control on these processes by vegetation depends on climate, soil, and other catchment characteristics. One of the difficulties in predicting changes in streamflow at a monthly or daily time step is to decide on a method that can capture the characteristics of the streamflow time series in the simplest way possible. This is important when comparing two time series as the difference needs to be quantified using well-defined statistics, such as the mean and the variance. A commonly used approach for making such predictions is to rely on detailed physically based models or statistical models derived from paired-catchment studies (Vertessy et al., 1993; Scott
These methods are either difficult to apply due to the extensive data requirements or constrained by local data, so an alternative approach is required.

An alternative way to evaluate the effect of afforestation on a catchment’s streamflow is to examine changes in a catchment’s FDC following a change in forest cover (Burt and Swank, 1992) rather than the time series itself. In doing this, the auto-correlation structure of the streamflow time series is ignored. A FDC represents the relationships between the magnitude and frequency of streamflow for a catchment and provides an estimate of the percentage of time a given flow is equalled or exceeded. The adoption of the FDC as a method to summarise the key features of a time series of streamflow, allows the identification of differences between the statistical distributions of two streamflow timeseries. Another useful feature of a FDC is its ability to display flow variability. It also has direct application in hydrology for hydropower, water allocation, and water quality management (Vogel and Fennessey, 1995). Most studies involving FDC analysis aim to provide information on the relationships between flow and frequency for catchments under static land-use (Fennessey and Vogel, 1990). However, the main aim of this chapter is to develop a procedure for predicting responses in a catchment’s FDC following a change in forest cover. This requires identification of an appropriate model that can be manipulated to reflect observed responses within a procedure that is simple enough for practical use. This chapter describes the development of such a methodology to predict how a FDC based on daily data will change following a change in forest cover.

In this chapter, we first develop a method to predict changes in FDCs without reference to any observed data but drawing on the Zhang curves (Zhang et al., 2001) and Best’s FDC parameterisation (Best et al., 2003b). This method is then tested by using the data from the pre-treatment period and the Zhang curves as input to predict the post-treatment FDC and then comparing the predicted and observed FDC in the post-treatment period.

### 6.2 Data

Streamflow, rainfall and potential evapotranspiration data from 17 experimental catchments have been used in this chapter. These comprise of 13 afforestation catchments and 4 deforestation catchments. Apart from the Pine Creek catchment, all catchments are part of paired catchments studies. In this application, only the treated catchments have been used. Chapter 3 provides details of the experimental catchments.
6.3 Methodology
The procedure outlined below to adjust the FDC for changes in forest cover uses a “top-down” or downward approach to model development (Sivapalan et al., 2003). This approach differs from physically based modelling in that it tries to capture the overall response of a catchment based on the analysis and interpretation of the observed data. The level of process understanding included in a model is based on analysis of the data rather than the notion that a particular process must be included in the modelling. The mean annual water balance model of Zhang et al. (1999) and Zhang et al. (2001) is a good example of the top-down or downward modelling approach. It provides a practical tool known as the “Zhang curves” for predicting the long-term consequences of afforestation or deforestation on mean annual evapotranspiration at the catchment scale. This model is based on observed data and has an advantage over traditional process based models in that the required input data (mean annual rainfall and percentage forest cover) are readily available at both catchment and regional scales. By linking the Zhang curves model to a parameterised FDC, a methodology is developed that allows the impact of forest change on the FDC to be predicted.

The linkage between the Zhang curves and the parameterised FDC comes from the knowledge that the area under the FDC must be equal to the mean annual streamflow (Figure 6–1). While the Zhang curves produce an estimate of the mean annual evapotranspiration, it is easy to estimate mean annual streamflow by differencing the mean annual rainfall and mean annual evapotranspiration. Figure 6–1 shows the link between the change in streamflow predicted from the Zhang curves and the difference between two FDCs for different forest covers.
Chapter 6: Adjusting flow duration curves for changes in forest cover

Figure 6–1: Linking the Zhang curves to the FDC. Using the Zhang Curves (a), the change in mean annual streamflow can be predicted ($\Delta$ Streamflow). This is linked to the FDC (b) as the shaded area between the FDC for Grass and FDC for forest is equal to $\Delta$ Streamflow.

To adjust the FDC for a change in forest cover it is useful to parameterise the FDC. The parameterisation should capture the key features of the curve and the parameter values should be able to be linked to known catchment properties and/or predicted changes in streamflow. The parameterisation used in this chapter is the one described in Chapter 5 and in Best et al. (2003b). It has five parameters. The method normalises the FDC to have $Q_{50} = 1$ and $\text{CTF} = 0$, and then fits the remaining three-parameters ($s$, $c_u$, $c_l$) to the normalised FDC (NFDC). Figure 6–2 illustrates the procedure used to normalise the FDC of perennial and ephemeral streams. Firstly, the cease-to-flow (CTF) percentile is established (Figure 6–2a). The CTF percentile is defined as the ratio of the number of non-zero flow days to the total number of days. In this chapter, a non-zero flow day is assumed to be the one in which the flow is greater than or equal to a specified threshold value ($Q_{TV}$ - adopted here as 0.001 mm/day). A FDC is then constructed using only days for which flow is greater than the threshold value as streamflow measurements below this value are considered insignificant (Figure 6–2b). Next, the FDC for the days with flow is standardised by dividing all flow values by the conditional median flow (Figure 6–2c). The conditional median is defined as the median flow of the days on which flow occurs. Finally, the FDC is plotted in lognormal space (Figure 6–2d) to produce a normalised FDC (NFDC). This normalisation procedure results in all of the NFDCs intersecting the origin (Figure 6–2d).
Figure 6–2: Normalising the FDC to achieve common parameter space

In Chapter 5, three models were outlined to describe the shape of the NFDC. The three models were compared to determine which one offered the most robust fit to a range of flow duration curves. Equation 6-1 was the recommended model by Best et al. and is the parameterisation of the FDC used in this chapter. This model has five-parameters and involves fitting exponential curves to the upper and lower sections of the NFDC.

$$
\hat{y} = \begin{cases} 
Q_{50} \left( \frac{s}{10^{c_i}} \left[ \exp \left( F^{-1} \left( \frac{x}{CTF} \right) c_i \right) - 1 \right] \right) 
& \text{for } x \leq \frac{CTF}{2} \\
Q_{50} \left( \frac{s}{10^{c_i}} \left[ \exp \left( F^{-1} \left( \frac{x}{CTF} \right) c_i \right) - 1 \right] \right) 
& \text{for } \frac{CTF}{2} < x < CTF \\
0 
& \text{for } x \geq CTF
\end{cases}
$$

Equation 6-1

where $\hat{y}$ is the predicted flow, $F^{-1}$ is the inverse of the standard normal cumulative distribution, $Q_{50}$ is the median of the non-zero flow days, $CTF$ is the cease-to-flow
percentile (expressed as a percentage), \( x \) is a flow percentile value (0.01-99.99%) and \( s, c_u, c_l \) are curve fitting parameters. The \( s, c_u \) and \( c_l \) parameters relate to different sections of the FDC, \( s \) being the slope at the origin of the NFDC and \( c_u \) and \( c_l \) are the exponents of the upper and lower sections of the NFDC, respectively.

To develop a methodology to adjust the FDC for a change in forest cover, a procedure is required to adjust the FDC parameters in response to changes in mean annual streamflow. This allowed predictions based on mean annual streamflow to be linked to the daily FDC. Figure 6–3 summarises the six key steps for adjusting the FDC for forest cover change. These steps are described in detail in Sections 6.3.1 to 6.3.7.

The data required to use the methodology are (i) daily flow data under static land use conditions, (ii) daily rainfall data, (iii) daily potential evapotranspiration (PET) data, (iv) current percentage forest cover, and (v) proposed percentage forest cover.

Figure 6–3: Flow chart showing the key steps in adjusting the FDC for land use change.
6.3.1 Step 1: Estimating change in mean annual streamflow

Given a proposed change in forest cover, the change in streamflow can be estimated using the Zhang curves. These were developed to estimate the change in evapotranspiration when changing from one vegetation type to another. Assuming that the change in the soil water storage and recharge terms is negligible over the long term, the water balance can be simplified to streamflow equalling rainfall minus actual evapotranspiration. Thus, an estimate of mean annual evapotranspiration can be changed to an estimate of mean annual streamflow. Figure 6–4 shows the relationship between mean annual rainfall and mean annual streamflow based on the equations developed by Zhang et al. (1999). Equation 6-2 is the expression for calculating the evapotranspiration under a given percentage forest cover and Equation 6-3 gives the resulting streamflow (Zhang et al., 2001).

\[
ET_f = \left( f \frac{1+2 \frac{1410}{P}}{1+2 \frac{1410}{P} + \frac{P}{1410}} + (1-f) \frac{1+0.5 \frac{1100}{P}}{1+0.5 \frac{1100}{P} + \frac{P}{1100}} \right) P \\
\]

where, \( f \) is the fraction of forest cover, \( P \) is the mean annual rainfall (mm), and \( ET_f \) is the estimated actual total annual evapotranspiration (mm) for a specific percentage forest cover \( f \).
Chapter 6: Adjusting flow duration curves for changes in forest cover

\[ \text{WY}_f = P - ET_f \]  \hspace{1cm} \text{Equation 6-3} \\

where \( \text{WY}_f \) is the predicted mean annual streamflow, \( P \) is the mean annual rainfall and \( ET_f \) is the mean annual evapotranspiration as calculated from Equation 6-2.

The streamflow for the proposed forest cover is calculated from the proportional change in streamflow predicted from the Zhang curves (Equation 6-2) and the observed mean annual streamflow for the current vegetation type.

\[ \text{WY}_{\text{proposed}} = \text{WY}_{\text{observed, current}} \left[ 1 + \left( \frac{\text{WY}_{\text{Zhang, proposed}} - \text{WY}_{\text{Zhang, current}}}{\text{WY}_{\text{Zhang, current}}} \right) \right] \]  \hspace{1cm} \text{Equation 6-4} \\

where, \( \text{WY}_{\text{proposed}} \) is the predicted streamflow under proposed forest cover, \( \text{WY}_{\text{observed, current}} \) is the observed streamflow under current forest cover, \( \text{WY}_{\text{Zhang, current}} \) and \( \text{WY}_{\text{Zhang, proposed}} \) are the values of \( \text{WY}_f \) (Equation 6-3) predicted from the Zhang curves under current forest cover and proposed forest cover respectively.

### 6.3.2 Step 2: Parameters of annual flow duration curves

The daily annual FDC is defined as the FDC for a complete year constructed from the daily flow data for that year. To minimise the difference between the soil water storage at the beginning of each year, a water year has been adopted as the annual time unit. In determining the water years, it was decided not to split either the wet or the dry flow periods to ensure that there is minimal difference in water storage between years. Therefore, in this chapter, the start of the water year is defined as the first day of the month following the cumulative average driest three-month period. For example, if February, March and April gave the driest three-month period on average, then the water year would start on May 1\(^{st}\) and finish on April 30\(^{th}\). Once the start of the water year is determined, the observed flow data is divided into water years, the observed FDCs are calculated and the FDC model parameters determined for each water year.

The FDC parameters are the CTF percentile, the conditional median and three curve-fitting parameters for the NFDC, referred to as the slope, upper exponent and lower exponent. The slope, upper exponent and lower exponent are \( s \), \( c_u \) and \( c_l \) in Equation 6-1, respectively. The CTF percentile and the conditional median are determined directly from the observed data while the curve fitting parameters are fitted using a two stage iterative process:
1. The slope and then the upper and lower exponents are adjusted to minimise the sum of squared error of the difference between the observed and fitted FDCs.

2. The upper exponent is then adjusted to achieve a mass balance between the fitted curve and the observed data.

The quality of the fit of the FDC to the data is judged using the coefficient of efficiency, $E$, calculated in the log domain (Nash and Sutchiffe, 1970).

\[
E = 1 - \frac{\sum_{i=1}^{CTF} (\log(O_i) - \log(P_i))^2}{\sum_{i=1}^{CTF} (\log(O_i) - \log(\bar{O}))^2}
\]

Equation 6-5

here $O$ is the observed percentile flow and $P$ is the predicted percentile flow. The closer the coefficient of efficiency is to one the better the fit. The logarithm of the values is used to give more weight to low flow values. $E$ is calculated only between the first percentile and the CTF percentile, thus zero flows are not considered. Only year with $E \geq 0.97$ are used in the subsequent analysis (to ensure only robust estimates are used).

Once the parameters for each annual FDC are determined, the representative values of $s$ and $c_u$ are estimated as the mean of each of the $s$ and $c_u$ values for all the pre-treatment years with $E \geq 0.97$. It is initially assumed that these parameters remain unchanged following a change in forest cover. This is because very few catchments showed changes in these parameters in the analysis undertaken Chapter 5 (Table 5-4).

6.3.3 Step 3: Cease-to-flow percentile or 95th percentile flow

Chapter 4 and Brown et al. 2005 (Chapter 2) showed that vegetation has a greater affect on the lower flow part of the FDC than the higher flow part. The low flows (represented by the 95th percentile for perennial streams and the CTF percentile for ephemeral streams) are controlled by recharge, which is influenced by interception, soil type and depth, the ability of vegetation to extract water from the soil moisture store, and the pattern of rainfall. When a catchment’s vegetation is changed, rainfall interception and the amount of water extracted from the soil moisture store by the vegetation will be affected. The Zhang curves provide an estimate of how the total evapotranspiration may change as forest cover changes. However, it does not indicate how vegetation affects the individual processes, such as interception loss and transpiration from the soil water store. In Australia, it is recognised that clearing of
native vegetation for agriculture has led to increased recharge and hence increased groundwater levels. These elevated groundwater levels are the result of lower total actual evapotranspiration from agricultural crops and pastures compared with forests because of the crops and pastures not being able to extract water from deeper in the soil profile. To predict the change in 95th percentile or cease to flow percentile a simple single bucket model is used.

### 6.3.4 Adjusting the 95th or Cease to Flow percentile

The 95th or CTF percentile is adjusted by:

1. Calibrating the bucket model, described in Section 6.3.4.1 to the pre-treatment flow data to achieve mass balance and match the 95th or CTF percentile. This requires the recession constant, k, and the two parameters that define the size of the bucket, $S_{\text{max}}$ and $S_{\text{ET}}$ to be determined. An initial estimate of the recession constant ($k$) is determined from the observed hydrographs as outlined in section 6.3.4.2 while $S_{\text{max}}$ and $S_{\text{ET}}$ are determined to ensure mass balance and match 95th or CTF percentile. However, if the requirements of mass balance and matching the 95th or CTF percentile cannot be reached using the estimated value of $k$, then $k$ is adjusted until these requirements are met.

2. Adjusting the model parameter ($S_{\text{ET}}$) to obtain mass balance with the mean annual flow for the new vegetation cover as predicted using the Zhang Curves in Step 1 (Section 6.3.1). The procedure used to adjust the bucket size and obtain new values of the 95th percentile flow is described in Section 6.3.4.3.

### 6.3.4.1 Developing a simple bucket model

Cease-to-flow conditions occur when the water table is below the stream invert. A simple bucket can be used to estimate the change in low flow or CTF percentile. The simplest conceptualisation of this system is a single bucket model where the relationship between precipitation ($P$), evapotranspiration ($ET$) and streamflow ($Q$) is mediated by a single combined soil and groundwater storage (hereafter referred to as the soil water store). The conceptual model is shown in Figure 6–5. The maximum soil water storage, $S_{\text{max}}$, represents the maximum soil water possible above the baseflow threshold ($S_{\text{base}}$). A threshold below which there is zero evapotranspiration is given by $S_{\text{ET}}$. The soil water storage at which streamflow ceases is given by $S_{\text{base}}$. In the calculations $S_{\text{base}}$ is set to Zero, $S_{\text{max}}$ must be positive, while $S_{\text{ET}}$ can be either negative or positive. When $S_{\text{ET}}$ is negative, ET can still occur even when the soil water is below $S_{\text{base}}$. 

---

112
Figure 6–5: Simple bucket model used to model the percentage of time flow occurs. Here, P is precipitation, I is interception, ET is the Evapotranspiration, \( Q_{\text{direct}} \) is the direct runoff, \( Q_{\text{base}} \) is the baseflow, \( S_{\text{base}} \) is the reference point of the model and is set to a value of 0, \( S_{\text{max}} \) and \( S_{\text{ET}} \) are the parameters of simple bucket model.

The water balance of the bucket model is given by

\[
S_{t} = S_{t-1} + P_{t} - I_{t} - ET_{t} - Q_{\text{direct}} - Q_{\text{base}} \tag{Equation 6-6}
\]

here \( S_{t-1} \) is the storage at the previous time step, \( P_{t} \) is the rainfall, \( I_{t} \) is the interception, \( ET_{t} \) is the actual evapotranspiration, \( Q_{\text{direct}} \) is the surface or quick flow and \( Q_{\text{base}} \) is the baseflow.

The order in which water is added and subtracted from the bucket to achieve the storage at the end of a day is important. It should represent the order in which the processes occur. Therefore, the interception loss is removed from the rainfall and the remaining rainfall is added to the storage in the bucket. If the storage exceeds \( S_{\text{max}} \) then direct runoff occurs and is calculated as in Equation 6-7. Once \( Q_{\text{direct}} \) has been determined, \( ET \) is calculated based on Equations 6-8 to 6-10. After \( ET \) has been estimated, \( Q_{\text{base}} \) can be computed as shown in Equations 6-11 and 6-13. Thus, the storage at the end of a day can be calculated.

\[
Q_{\text{direct}} = \begin{cases} 
0 & S_{t-1} + P - I \leq S_{\text{max}} \\
S_{t-1} + P - I - S_{\text{max}} & S_{t-1} + P - I \geq S_{\text{max}}
\end{cases} \tag{Equation 6-7}
\]

To account for the different rates of interception between grasses and forest, an interception store has been included in the model. For simplicity, interception has been taken as a constant (Farmer et al., 2003) taking a value of 1mm of rainfall for fully
grassed catchments and 4 mm for fully forested catchments. Linear interpolation between these two values has been used to allow for the partial forest cover in a catchment.

The ET of vegetation is a function of soil water storage in the root zone, leaf area index and potential evapotranspiration (PET). In order to keep the model as simple as possible and noting that the main interest is in predicting the impact of changing from agricultural crops or pasture to plantation forestry, the relationship between actual ET and PET shown in Figure 6–6 has been adopted. A linear interpolation between the forest and grass curves has been adopted for partial forest cover in a catchment as shown in Equation 6-8 to 6-10.

**Figure 6–6: ET function proposed by Farmer et al., 2003 and adopted in the simple bucket model.**

\[
ET_{\text{grass}} = \begin{cases} 
    PET_t \times RSWS_t, & RSWS_t > 0 \\
    0, & RSWS_t \leq 0 
\end{cases} \\
ET_{\text{forest}} = \begin{cases} 
    \frac{PET_t}{RSWS_t}, & RSWS_t > 0.4 \\
    \frac{0.4 \times PET_t}{RSWS_t}, & 0.4 \geq RSWS_t \geq 0 \\
    0, & RSWS_t < 0 
\end{cases}
\]

Equation 6-8
Here RSWS is the relative soil water storage and is given by

\[
RSWS = \frac{(S_{t-1} + P_t - Q_{direct}) - S_{ET}}{S_{max} - S_{ET}}
\]

Equation 6-9

\(ET\) is determined from Equation 6-10

\[
ET_{total} = fET_{forest} + (1 - f) ET_{grass}
\]

Equation 6-10

Here \(f\) is the percentage forest cover in the catchment

Assuming the baseflow recession curve can be expresses by

\[
Q_t = Q_{t-1} \exp(-\alpha) = Q_{t-1}k
\]

Equation 6-11

Where, \(Q_t\) is the discharge at time \(t\), \(Q_{t-1}\) is the discharge at the pervious time step, and the term \(\exp(-\alpha)\) is replaced by the recession constant, \(k\). This recession constant, \(k\), is estimated to be between 0.93 and 0.995 for baseflow for a daily time step (Nathan and McMahon, 1990). Integrating the above expression reveals that

\[
Q_t = -\ln(k) S_t
\]

Equation 6-12

Therefore,

\[
Q_{base} = \begin{cases} 
0 & S_{t-1} + P - I - Q_{direct} - ET_t \leq S_{base} \\
-\ln(k)[(S_{t-1} + P - I - Q_{direct} - ET_t) - S_{base}] & S_{t-1} + P - I - Q_{direct} - ET_t \geq S_{base}
\end{cases}
\]

Equation 6-13

As shown in Equation 6-13, the baseflow is calculated assuming a simple linear storage model. This requires an estimation of the recession constant. As the bucket model is calibrated to observed flow, the recession constant has been estimated from the observed time series of daily streamflow following the procedure outlined in Section 6.3.4.2. The recession constant is estimated from the observed time series, as this will give a more robust initial estimate of this parameter than calibrating it along with the other parameters. In most catchments, it was not necessary to alter \(k\) to achieve mass balance and fit the low flow section of the FDC. While it may have been possible to obtain better results using a nonlinear recession model, such as those described by Tallaksen (1995) or Brutsaert and Nieber (1977). It is considered that there is more experience in the application of the linear storage model adopted, which has shown that it is applicable over the range of catchments considered in the analysis. The
added complexity of non-linear models would also reduce the simplicity of the bucket model, as more parameters would be required to be estimated and adjusted.

6.3.4.2 Developing a method to estimate the recession constant

There are numerous methods available for estimating baseflow recession constant, \( k \). Many methods rely upon plotting recessions on a logarithmic axis and using an averaging technique (Nathan and McMahon, 1990). Others use filtering methods to separate the baseflow component of flow and then estimating the recession from the filtered baseflow (CRC for Catchment Hydrology, 1996). One of the major problems with these techniques is making a distinction between the components of the recession, surface flow, interflow and baseflow. The distinction between interflow and baseflow is very difficult to estimate. Quite often, these methods are subjective and the result for the same time series differs depending on the practitioner. As the method outlined in this chapter aims to adjust the FDC in a reproducible manner, a methodology for determining recession constant is required that does not depend on the subjective decisions of the practitioner.

The method developed to determine the recession constant works by identifying the three major components of a hydrograph recession namely, surface flow, interflow and baseflow (Figure 6–7). When plotted in log space, there are six possible combinations of the components of the streamflow recession (see Figure 6–8):

1. Surface flow only
2. Surface and interflow
3. Surface, interflow and baseflow
4. Interflow only
5. Interflow and baseflow
6. Baseflow only

According to Nathan and McMahon (1990), it is possible to distinguish between the parts of a recession based on the values of the different recession constants. Typically for daily data the range for recession constants have been found to be, 0.2 – 0.8 for surface flow, 0.7 - 0.94 for interflow and 0.93 - 0.995 for baseflow, thus it should be possible to separate out the baseflow recession from surface flow and interflow based on the slope when plotted in logarithmic space (Figure 6–8)
Once the recessions are identified from the time series, they are classified into one of the six categories based on the slope. Recessions that fall into categories without a baseflow component are rejected (Categories 1, 2 and 4). The remaining recessions are then analysed by fitting lines of best fit to identify the baseflow component.

The method works by:

1. Identifying every recession over 5 days in length. A recession is defined as a period of flow during which the flow is not increasing. Gaps and small rises in the streamflow time series cause the start of a new recession.
2. Identifying and removing the surface flow component. We first calculate a recession constant for each segment in the recession. A segment is defined as being two adjacent points on the recession at the recording interval of the hydrograph (i.e. daily). The segments identified as having a recession constant less then 0.8 is considered as surface flow. All segments above the lowest segment that have a recession constant less than 0.8 are also considered as surface flow. The threshold value of 0.8 for surface flow is based on the recommendations in Nathan and McMahon (1990).

3. Separation of interflow and baseflow. The baseflow and interflow are separated by determining the change in slope in the recession. This is achieved by fitting two lines through the natural log of the flow values in an iterative manner as shown in Figure 6–9. A line, Line 1, is fitted through the first two points of the recession and the $R^2$ is determined. A second line, Line 2, is fitted through the remaining points plus the last point in Line 1 and the $R^2$ of this line is determined (Figure 6–9A). The weighted $R^2$ is then determined by multiplying the $R^2$ for Line 1 with the number of points in Line 1 and adding this to the $R^2$ for Line 2 multiplied by the number of points in Line 2 and diving by the total number of points. This procedure is followed along the entire length of the recession, increasing the number of points in Line 1 and deceasing the number of point in Line 2 until Line 1 is fitted through the entire recession (Figure 6–9 B – D). The maximum weighted $R^2$, referred to as the change factor, is then determined (Figure 6–9C). This identifies the point where the slope of the recession changes.

4. Once the point of change is determined, the recession constant for both sections of the recession can be determined. If both sections of the recession have a recession constant greater than 0.93 (based on the lower limit for recession constant for baseflow in Nathan and McMahon, 1990), then potentially the entire recession is baseflow. However, if the difference in the recession constants of the two sections is greater than 0.005, then the recession is considered to have two distinct components and the upper section is considered interflow and lower section is baseflow. If the difference in recession constant is less than 0.005 and both sections have a recession constant greater then 0.93 then all the points in the recession are considered baseflow and the recession constant is determined for the entire recession (excluding any points considered as surface flow). If the lower section of the
Chapter 6: Adjusting flow duration curves for changes in forest cover

recession has a recession constant, less than 0.93, then all points in the recession are considered to be interflow.

5. The previous steps are repeated for all recessions more than 5 days in length. The overall baseflow recession constant is then determined by taking a weighted average of the recession constants for each of the individual recessions based on the length of each recession. i.e. the recessions with the greatest number of days gets the greatest weighting.

![Graphs showing the procedure for determining the change from interflow to baseflow for a recession 28 days in length.](image)

Figure 6–9: Procedure for determining the change from interflow to baseflow for a recession 28 days in length. A, shows Line 1 fitted through the first 2 points and Line 2 fitted through the last 27 points. B, shows Line 1 fitted through the first 3 points and Line 2 fitted through the remaining 26 points. C, shows the two lines that have the maximum weighted $R^2$ or change factor (9 points in Line 1 and 20 points in Line 2). D shows the Line 1 fitted through the entire recession.

The result is a single number that represents the baseflow recession constant. This is used in Equation 6-12 to control the baseflow from the bucket model at each time step.

When applying the model for changes in vegetation, it is assumed that the changes do not affect $k$, $S_{max}$ and $S_{base}$ (reference point) and that only $S_{ET}$ will be affected. Under conditions where a stream goes from being perennial to ephemeral, it is anticipated that the $S_{ET}$ would change from being above $S_{base}$ to below $S_{base}$. $S_{base}$ provides a point of reference for both $S_{max}$ and $S_{ET}$ and is set to zero.

6.3.4.3 Adjusting the bucket size for a change in forest cover

The approach of using a simple bucket model is driven by the need to be able to predict the impact of vegetation on the low flow section of the FDC. Changes to this
section of a FDC are primarily driven by changes in baseflow. The ability of deep-rooted vegetation such as forests to extract water from the soil store is much greater than for short rooted grass. The bucket model is initially calibrated to the observed flow time series for the period of initial vegetation cover. The calibration is undertaken by adjusting, $S_{\text{max}}$, $S_{\text{ET}}$ and, where required, $k$. $k$ is only adjusted if the model could not match the 95th or CTF percentile and achieve mass balance without changing $k$ from its initial value. The calibration ensures mass balance is within 5% and the CTF percentile of the 95th percentile flow is within 1% of the observed value. To adjust the bucket for a change in forest we need to adjust depth to which the vegetation can extract water via transpiration from the bucket. This is achieved by assuming that after a change in vegetation the $S_{\text{max}}$ and $k$ parameters of the bucket model are unchanged. This means that to match the change in streamflow predicted by the Zhang curves, the only parameter that can be adjusted is $S_{\text{ET}}$ which is the threshold value for which evapotranspiration ceases. Increasing $S_{\text{ET}}$ results in greater streamflow from the bucket, which would be anticipated following a reduction in forest cover. Decreasing $S_{\text{ET}}$ results in a reduction in streamflow, this would be expected following an increase in forest cover. Recall, however, that the interception store capacity also changes in response to forest cover change, as it is calculated directly from the percentage forest cover.

Once $S_{\text{ET}}$ is adjusted to achieve mass balance with the mean annual streamflow under the proposed forest cover (predicted using the Zhang Curves during step 1). The CTF percentile and/or the 95th percentile flow can be determined from the daily flow time series output from the bucket model for the period when the catchment is under the new forest cover. In some cases $S_{\text{ET}}$ needs to be moved in the opposite direction of that expected for the change in forest cover (i.e. $S_{\text{ET}}$ increased when the forest cover increased), this is because the change in interception and ET function associated with new forest cover cause sufficient changes in streamflow without a need to change the bucket size. When this occurred, the $S_{\text{ET}}$ value is not altered.

6.3.5 Step 4: Conditional Median (initial estimate)

Once the CTF percentile for the new percentage forest cover is determined, the next parameter to be adjusted is the conditional median. This is achieved by creating catchment specific relationships between the annual conditional mean and the annual conditional median of the observed time series. The annual conditional mean and median are determined from the streamflow during each water year defined in Step 2 (Section 6.3.2).
Chapter 6: Adjusting flow duration curves for changes in forest cover

Figure 6–10 shows a typical relationship between the annual conditional mean and conditional median streamflow for the Bosboukloof catchment. Once the relationship between the conditional mean and conditional median streamflow is established, the new conditional median is estimated based on the estimated mean annual flow under the new forest cover. This method is used provided the coefficient of determination ($R^2$) is greater than 0.6. If the $R^2$ value is less then 0.6, the regression relationships between the conditional mean and conditional median is considered too poor to give meaningful results and therefore the methodology should not be used to adjust a catchment’s FDC for forest cover change. The conditional mean for the new forest cover conditions is determined by dividing the mean annual flow predicted in Step 1 by the CTF percentile for the proposed forest cover (predicted from Step 3).

![Figure 6–10: Typical relationship between the conditional mean and conditional median streamflow for Bosboukloof catchment.](image)

### 6.3.6 Step 5: Lower exponent (initial estimate)

The determination of the lower exponent ($c_l$) depends on the nature of the streamflow at the catchment outlet. For ephemeral streams, the estimate of the lower exponent is based on the slope ($s$) of the NFDC and the knowledge that the CTF percentile will equal the threshold value (adopted here as 0.001 mm/day). For perennial streams the estimate of the lower exponent based on the 95th percentile flow from the bucket model. With an estimate of the CTF or 95th percentile flow and the slope, we can rearrange Equation 6-1 to determine the value of the lower exponent that is required to intercept the CTF percentile or the 95th percentile flow. Equation 6-14 and Equation 6-
15 give the expressions to determine the lower exponent for ephemeral and perennial streams respectively.

$$\frac{1}{s} \log \left( \frac{Q_{TV}}{Q_{50}} \right) = \frac{1}{c_l} \left( \exp \left( F^{-1}(0.9999)c_l \right) - 1 \right)$$  \hspace{1cm} \text{Equation 6-14}

$$\frac{1}{s} \log \left( \frac{Q_{95}}{Q_{50}} \right) = \frac{1}{c_l} \left( \exp \left( F^{-1}(0.95)c_l \right) - 1 \right)$$  \hspace{1cm} \text{Equation 6-15}

Here, $s$ is the slope and $c_l$ is the lower exponent as defined in Equation 6-1, $F^{-1}$ is the inverse of the standard normal cumulative distribution, $Q_{50}$ is the median of the non-zero flow days. $Q_{TV}$ is the threshold value below which it is assumed zero (taken as 0.001 mm/day), $Q_{95}$ is the 95th percentile estimated from the bucket model. As it is not possible to determine the inverse of the standard normal cumulative distribution of a value of 1, 0.9999 is adopted for ephemeral streams (Equation 6-14). While the section of 0.001 mm/day for $Q_{TV}$ and 0.9999 in Equation 6-14 are arbitrary, the results are insensitive to the choice of these values. For perennial streams the calculation is based on the 95th percentile flow, hence the inverse of the standard normal cumulative distribution of 0.95 is adopted (Equation 6-15).

### 6.3.7 Step 6: Achieving mass balance

The slope ($s$) and upper exponent ($c_u$) are estimated in Step 2 by taking the mean of the annual slopes and upper exponents. The conditional median for the new percentage forest cover is then calculated from the recession relationship between the conditional mean and median from the observed flow data (Step 4), the lower exponent is then calculated based on the combination of the output from the bucket model and mean slope (Steps 2, 3 and 5). These parameters provide an initial estimate of the FDC under the new forest cover. However, it is important that the area under the FDC equals the mean annual streamflow predicted by Step 1. If the area under the FDC does not equal the predicted mean annual streamflow the conditional median, $P_{50}$, is adjusted to ensure mass balance. The lower exponent is then recalculated using Equation 6-14 or Equation 6-15 to ensure that the lower portion of the FDC intersects either the 95th percentile flow or the CTF percentile determined from the bucket model. This adjustment of the lower exponent has minimal effect on the mass balance.
6.4 Results
The results of the FDC adjustment methodology have been assessed using two approaches. The first uses the observed change in mean annual streamflow between the pre-treatment (calibration) and post-treatment (new equilibrium) periods. This allows the FDC adjustment methodology to be separated from the errors in predicting the change in mean annual streamflow from the Zhang curves. Section 6.4.1 describes the results using the observed change in streamflow in the paired catchment studies. Section 6.4.2 presents the results including the predictions from the Zhang curves. Table 6-1 provides details of rainfall, observed mean annual streamflow and predicted mean annual streamflow from the Zhang Curves for the calibration and new equilibrium periods. To illustrate how the observed results compare to the Zhang Curves, Figure 6–11 shows the Zhang curves and the observed streamflow for catchments that have at least 70% change in forest cover and less than 20% difference in rainfall between the calibration and new equilibrium period. This helps to illustrate how the Zhang Curves are likely to impact on the FDC Results. The impact of the Zhang Curves is further investigated in Section 6.4.2.

![Figure 6–11: Zhang curves for 100% grass and 100% forest with observed change in streamflow shown for a subset of the experimental catchments. Only catchments with between 70 - 100% change in forest cover and a less then 20% difference between the rainfall during the calibration and equilibrium period have been shown.](image-url)
Table 6-1: Comparison between the observed changes in streamflow and changes predicted from the Zhang curves

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Calibration Period</th>
<th>New equilibrium</th>
<th>Reduction in streamflow (Grass to Forest)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Streamflow</td>
<td>% forest</td>
<td>Observed</td>
</tr>
<tr>
<td>Red Hill</td>
<td>965</td>
<td>0%</td>
<td>294</td>
</tr>
<tr>
<td>Pine Creek</td>
<td>845</td>
<td>0%</td>
<td>110</td>
</tr>
<tr>
<td>Glendhu</td>
<td>1309</td>
<td>0%</td>
<td>827</td>
</tr>
<tr>
<td>Cathedral Peak II</td>
<td>1412</td>
<td>0%</td>
<td>862</td>
</tr>
<tr>
<td>Cathedral Peak III</td>
<td>1654</td>
<td>0%</td>
<td>899</td>
</tr>
<tr>
<td>Bosboukloof</td>
<td>1057</td>
<td>0%</td>
<td>544</td>
</tr>
<tr>
<td>Biesievlei</td>
<td>1047</td>
<td>0%</td>
<td>621</td>
</tr>
<tr>
<td>Tierkloof</td>
<td>1350</td>
<td>0%</td>
<td>1093</td>
</tr>
<tr>
<td>Lambrechtsbos A</td>
<td>1144</td>
<td>0%</td>
<td>568</td>
</tr>
<tr>
<td>Lambrechtsbos B</td>
<td>1169</td>
<td>0%</td>
<td>517</td>
</tr>
<tr>
<td>Mokobulaan A</td>
<td>906</td>
<td>0%</td>
<td>230</td>
</tr>
<tr>
<td>Mokobulaan B</td>
<td>934</td>
<td>0%</td>
<td>236</td>
</tr>
<tr>
<td>Westfalia D</td>
<td>1295</td>
<td>0%</td>
<td>386</td>
</tr>
<tr>
<td>Wight</td>
<td>1127</td>
<td>100%</td>
<td>199</td>
</tr>
<tr>
<td>Lemon</td>
<td>754</td>
<td>100%</td>
<td>18</td>
</tr>
<tr>
<td>Don</td>
<td>661</td>
<td>100%</td>
<td>13</td>
</tr>
<tr>
<td>Witklip 6</td>
<td>1215</td>
<td>100%</td>
<td>307</td>
</tr>
</tbody>
</table>
To determine if the assumption that the recession constant, k, does not change between pre and post treatment periods is valid, the mean k values for the calibration and new equilibrium periods were compared using the Student’s t-test. This analysis showed that in 12 of the 17 catchments there was no significant difference in the mean k values of the recessions during the calibration and new equilibrium periods. Figure 6-12 shows the variability of the k values between different recessions for all the afforestation catchments during the calibration and new equilibrium periods. While there are differences in the recession constant during the calibration and new equilibrium periods in many of the catchments, these differences were not statistically significant. In catchments with longer periods of record during both the calibration and new equilibrium periods there was little difference in the mean recession constant between the two periods.

![Figure 6–12: Spread in the recession constant (k) for each catchment showing the spread in the k values for the calibration and new equilibrium periods. The thick line represents the median, the box the 25th and 75th percentile and the whiskers the range of the recession constants for the individual recessions for each catchment. The red line shows the mean value of the recession constant.](image)

To test if the assumption that the relationship between conditional mean and median is similar before and after a change in forest cover, the partial F-test or Chow Test (Chow, 1960) was used to test the statistical difference between the empirical relationships developed between the conditional mean and conditional median during the calibration period and the new equilibrium periods. Of the 17 catchments, 13 showed that there
was no statistical difference in the relationships between the two periods at the 5% level. This indicates that these catchment specific relationships will hold most of the time. In some cases the assumption that the relationship between the conditional mean and conditional median does not change following a change in forest cover may lead to erroneous results. However, plotting the relationships for the calibration and new equilibrium periods showed us that only 1 of the 17 catchments (Witklip) showed a radical departure from the calibration period regression. The other three catchments that had statistically significant changes is a more of subtle change in slope causing extrapolation errors.

6.4.1 Observed flow during equilibrium period

Using the streamflow during the (post change) equilibrium period as the new mean annual streamflow, the bucket model described in Step 3 of the methodology is calibrated to the streamflow during the (pre change) calibration period. The size of the bucket is then adjusted using the $S_{ET}$ parameter to achieve mass balance with the flows during the equilibrium period. This ensures that mass balance is achieved for both the calibration and equilibrium periods for the different climatic sequences. The CTF percentile or the 95th percentile flow can then be determined from the bucket model for the equilibrium period. The overall model performance has been assessed using the coefficient of efficiency ($CofE$). Based on the recommendations in Chiew and McMahon (1993), the square root of the values has been taken to give an equal weighting to the low flows as shown in Equation 6-16

$$CofE = 1 - \frac{\sum_{i=1}^{N} (\sqrt{O_i} - \sqrt{P_i})^2}{\sum_{i=1}^{N} (\sqrt{O_i} - \sqrt{O_i})^2}$$

Equation 6-16

here, $CofE$ is the coefficient of efficiency, $O_i$ is the observed flow at percentile $i$ and $P_i$ is the predicted flow at percentile $i$ and $N$ is 99. Assessments have also been made of the models ability to predict the CTF percentile and the median flow. Table 6-2 provides a summary of results for all the paired catchment experiments using the observed mean annual flow during the equilibrium period to adjust the FDC. This shows us that when the observed mean annual water yield is used, the FDC adjustment methodology works well with 11 of the 17 catchments having coefficients of efficiency greater then 0.9. Figure 6–13 and Figure 6–14 show the third worst and third best fits for the change in streamflow respectively. To demonstrate how the mean annual streamflow estimates impacts on the predicted FDC, Figure 6–13 and Figure 6–
Chapter 6: Adjusting flow duration curves for changes in forest cover

14 also show the observed FDC during the calibration period, the parameterisation of the FDC for the equilibrium period, and the predicted FDC using the predicted change in mean annual flow from the Zhang curves.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>CTF predicted (%)</th>
<th>CTF observed (%)</th>
<th>Median Predicted (mm)</th>
<th>Median observed (mm)</th>
<th>coefficient of efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pine Creek</td>
<td>41</td>
<td>43</td>
<td>0.01</td>
<td>0.02</td>
<td>0.99</td>
</tr>
<tr>
<td>Red Hill</td>
<td>37</td>
<td>44</td>
<td>0.07</td>
<td>0.05</td>
<td>0.97</td>
</tr>
<tr>
<td>Don</td>
<td>27</td>
<td>32</td>
<td>0.06</td>
<td>0.07</td>
<td>0.96</td>
</tr>
<tr>
<td>Lemon</td>
<td>100</td>
<td>100</td>
<td>0.11</td>
<td>0.07</td>
<td>0.88</td>
</tr>
<tr>
<td>Wight</td>
<td>100</td>
<td>100</td>
<td>0.37</td>
<td>0.44</td>
<td>0.97</td>
</tr>
<tr>
<td>Glendhu</td>
<td>100</td>
<td>100</td>
<td>1.04</td>
<td>1.17</td>
<td>0.97</td>
</tr>
<tr>
<td>Bosboukloof</td>
<td>100</td>
<td>100</td>
<td>0.63</td>
<td>0.61</td>
<td>0.97</td>
</tr>
<tr>
<td>Biesievlei</td>
<td>100</td>
<td>100</td>
<td>0.47</td>
<td>0.48</td>
<td>0.97</td>
</tr>
<tr>
<td>Cathedral Peak II</td>
<td>100</td>
<td>100</td>
<td>0.40</td>
<td>0.41</td>
<td>0.87</td>
</tr>
<tr>
<td>Cathedral Peak III</td>
<td>100</td>
<td>100</td>
<td>0.63</td>
<td>0.52</td>
<td>0.96</td>
</tr>
<tr>
<td>Lambrechtsbos A</td>
<td>100</td>
<td>100</td>
<td>0.74</td>
<td>0.68</td>
<td>0.96</td>
</tr>
<tr>
<td>Lambrechtsbos B</td>
<td>73</td>
<td>100</td>
<td>0.77</td>
<td>0.29</td>
<td>0.51</td>
</tr>
<tr>
<td>Tierkloof</td>
<td>100</td>
<td>100</td>
<td>1.15</td>
<td>1.10</td>
<td>0.97</td>
</tr>
<tr>
<td>Mokobulaan A</td>
<td>1</td>
<td>10</td>
<td>0.65</td>
<td>0.06</td>
<td>0.16</td>
</tr>
<tr>
<td>Mokobulaan B</td>
<td>67</td>
<td>79</td>
<td>0.13</td>
<td>0.08</td>
<td>0.91</td>
</tr>
<tr>
<td>Westfalia</td>
<td>42</td>
<td>23</td>
<td>0.14</td>
<td>0.14</td>
<td>0.60</td>
</tr>
<tr>
<td>Witklip</td>
<td>100</td>
<td>99</td>
<td>0.39</td>
<td>0.74</td>
<td>0.47</td>
</tr>
</tbody>
</table>
Chapter 6: Adjusting flow duration curves for changes in forest cover

Figure 6–13: Third worst fit (coefficient of efficiency of 0.51) of the predicted FDC for the observed flows during the equilibrium period, shown in both linear and log space (Lambrechtsbos B).
Chapter 6: Adjusting flow duration curves for changes in forest cover

Figure 6–14: Third best fit of the predicted FDC (coefficient of efficiency of 0.97) for the observed flows during the equilibrium period, shown in both linear and log space (Glendhu).
6.4.2 Mean annual yield predicted using the Zhang curves

The results above show how the FDC methodology works when there is no error in the mean annual streamflow for the new forest cover. In most cases, however, the methodology will be used to predict the impact of proposed changes in forest cover for which and the mean annual streamflow for the new forest cover will be unknown. Therefore, it is necessary to assess how using the Zhang curves to predict the change in mean annual flow impacts on the results for the predicted FDC when compared to the observed FDC during the new equilibrium period. Table 6-3 shows the results for each catchment in terms of the observed and predicted CTF percentile, the conditional median and the coefficient of efficiency. Figure 6–15 and Figure 6–16 show the third worst and third best for the FDC when the Zhang curves are used to predict the change in mean annual water yield. Figures for all 17 catchments are provided in Appendix 6-A.

Table 6-3: Results from FDC adjustment methodology using predicted change from Zhang curves

<table>
<thead>
<tr>
<th>Catchment</th>
<th>CTF predicted</th>
<th>CTF observed</th>
<th>Median Predicted</th>
<th>Median observed</th>
<th>coefficient of efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pine Creek</td>
<td>39</td>
<td>43</td>
<td>0.03</td>
<td>0.02</td>
<td>0.61</td>
</tr>
<tr>
<td>Red Hill</td>
<td>68</td>
<td>44</td>
<td>0.15</td>
<td>0.05</td>
<td>-0.83</td>
</tr>
<tr>
<td>Don</td>
<td>29</td>
<td>32</td>
<td>0.07</td>
<td>0.07</td>
<td>0.96</td>
</tr>
<tr>
<td>Lemon</td>
<td>47</td>
<td>100</td>
<td>0.08</td>
<td>0.07</td>
<td>0.34</td>
</tr>
<tr>
<td>Wight</td>
<td>99</td>
<td>100</td>
<td>0.33</td>
<td>0.44</td>
<td>0.96</td>
</tr>
<tr>
<td>Glendhu</td>
<td>100</td>
<td>100</td>
<td>0.99</td>
<td>1.17</td>
<td>0.94</td>
</tr>
<tr>
<td>Bosboukloof</td>
<td>100</td>
<td>100</td>
<td>0.71</td>
<td>0.61</td>
<td>0.93</td>
</tr>
<tr>
<td>Biesievlei</td>
<td>100</td>
<td>100</td>
<td>0.52</td>
<td>0.48</td>
<td>0.95</td>
</tr>
<tr>
<td>Cathedral Peak II</td>
<td>100</td>
<td>100</td>
<td>0.73</td>
<td>0.41</td>
<td>0.46</td>
</tr>
<tr>
<td>Cathedral Peak III</td>
<td>100</td>
<td>100</td>
<td>0.77</td>
<td>0.52</td>
<td>0.90</td>
</tr>
<tr>
<td>Lambrechtsbos A</td>
<td>100</td>
<td>100</td>
<td>0.74</td>
<td>0.68</td>
<td>0.98</td>
</tr>
<tr>
<td>Lambrechtsbos B</td>
<td>100</td>
<td>100</td>
<td>0.60</td>
<td>0.29</td>
<td>0.39</td>
</tr>
<tr>
<td>Tierkloof</td>
<td>100</td>
<td>100</td>
<td>1.46</td>
<td>1.10</td>
<td>0.86</td>
</tr>
<tr>
<td>Mokobulaan A</td>
<td>100</td>
<td>10</td>
<td>0.17</td>
<td>0.06</td>
<td>-23.45</td>
</tr>
<tr>
<td>Mokobulaan B</td>
<td>100</td>
<td>79</td>
<td>0.22</td>
<td>0.08</td>
<td>-0.88</td>
</tr>
<tr>
<td>Westfalia</td>
<td>100</td>
<td>23</td>
<td>0.45</td>
<td>0.14</td>
<td>-6.04</td>
</tr>
<tr>
<td>Witklip</td>
<td>100</td>
<td>99</td>
<td>0.46</td>
<td>0.74</td>
<td>0.30</td>
</tr>
</tbody>
</table>
Figure 6–15: Third worst fit of the predicted FDC for the predicted mean annual flow (E = -0.88) during the equilibrium period (Mokobulaan B).
Figure 6–16: Third best fit of the predicted FDC for the predicted mean annual flow \( (E = 0.96) \) during the equilibrium period (Wight).

Figure 6–17 plots the observed streamflow against the predicted streamflow for the 5th, 50th and 95th percentiles for all 17 catchments. The legend in Figure 6–17 shows the coefficient of efficiency for the 5th, 50th and 95th percentiles (for both the observed change in mean annual streamflow and the predicted change in mean annual streamflow). We can see that the observed mean gives consistently better predictions for all three percentiles shown in Figure 6–17. Assuming that the 95th percentile is
representative of low flow conditions we can see that these flows are the most poorly predicted of the FDC, while the high flows (represented by the 5th percentile) are well predicted when the observed change in mean annual flow is used. The median flows (or 50th percentiles) are also well predicted when the observed change in mean annual flow is used in the prediction. Looking at the predictions based on the Zhang curves you can see that for the 5th and 50th percentiles, the predicted flows are consistently greater than the observed. This is consistent with Table 6-1 which showed a similar over-prediction in the changes in streamflow from the Zhang curves compared to the observed reductions.

Figure 6–17: Comparison between observed and predicted flows for the 5th, 50th and 95th percentiles. E values represent the coefficient of efficiency or the comparison to the 1 to 1 line, the closer the value of E to 1 the better the prediction.

Figure 6–18 provides a summary of the E values for each catchment and compares the two predicted FDCs (described in Table 6-2 and Table 6-3) with the E values of the parameterisation of the FDC. The parameterised FDC is used as a reference point as it represents the best possible fit of the predicted FDC that could be expected. The results show that when the observed change in mean annual streamflow is used to adjust the FDC, 11 of the 17 catchments have E values within ±10% of the parameterised E value. Only 4 of the 17 catchments have E values within ±10% of the parameterised E value when the Zhang curve is used to predict the change in mean flow.
Chapter 6: Adjusting flow duration curves for changes in forest cover

Figure 6–18: Comparison between coefficient of efficiencies (E) for the FDC Parameterisation, the predicted FDC using the observed change in mean annual flow (MAF), predicted FDC using the predicted MAF.

The results presented in Figure 6-18 illustrates the importance of having the correct mean annual streamflow. In 15 of the 17 catchments, the E value is reduced when the change in mean annual streamflow is predicted from the Zhang curves, although in 8 of the 15, the difference is small. In the one catchment with the improved E value (Lambrechtsbos A) when the Zhang curve predictions are used, it appears that the 95th percentile flow is better predicted improving the fit of the FDC. The remaining catchment (Don) shows difference in the E value between the two predicted FDCs.

6.5 Discussion

The results presented in this chapter illustrate how, as a result of forest cover change, an estimated change in mean annual water yield can be linked to a parameterisation of the FDC. This allows the change in a FDC resulting from a change in forest cover to be predicted. The model has been tested on a range of small experimental catchments and the results show how the model performs over a range of rainfalls and climate types. The following discussion is centred around:

1. the ability of the Zhang curves to predict the change in mean annual streamflow, and the implications for predicting the change in FDC,

2. the ability of the simple bucket model to predict the change in the CTF percentile or 95th percentile, and,
3. the impact of short periods of calibration data on the results of the FDC adjustment methodology.

One of the advantages of using the FDC to represent the change in the distribution of daily streamflow following a change in forest cover is that the area under the FDC must equal the mean annual streamflow. This allows the parameters of a FDC to be directly linked to an estimate of mean annual streamflow. In the methodology outlined above, the mean annual streamflow change due to a change in land use is estimated using the Zhang curves. These two curves are based on observed catchment data and represent close to 100% forest cover and 100% grass cover. While these curves are based on observed data, they are not based on catchments that have undergone a change in forest cover. Brown et al. (2005) presented a comparison of the Zhang curves to the observed change in streamflow in paired catchment studies. These results showed that for catchments going from grass to forest or forest to grass, the Zhang curves predicted the change in mean annual streamflow satisfactorily. However, the results in Section 6.4.1 and 6.4.2 show how the FDC adjustment procedure outlined is very sensitive to the estimated change in mean annual streamflow. This is because the key parameters (the conditional median and CTF or 95\textsuperscript{th} percentile flow) are dependent on the estimated mean annual streamflow. For example, if the Zhang curves overestimate the reduction in streamflow as the result of a forest cover increases, the parameters of the bucket model used to estimate the CTF point or 95\textsuperscript{th} percentile flow would be adjusted more than is necessary. This can result in the number of zero flow days being greater than is observed when the increase in forest cover occurs. It may also result in a prediction that a stream is likely to become ephemeral following an increase in forest cover, when in reality this may not happen.

While the Zhang curves represent one viable method of predicting the change in mean flow in response to forest cover change, it may not be the best in all circumstances and an advantage of the FDC adjustment methodology is that it can be combined with any method for estimating the change in mean annual streamflow for forest cover change.

The results presented in Table 6-1 and Figure 6–11, for both afforestation and deforestation experiments showed how the observed changes in streamflow from the paired catchment studies differ from the predicted changes estimated from the Zhang curves. Table 6-1 also shows the difference in rainfall between the calibration period and the new equilibrium period. In Table 6-1, it is observed that for 15 out the 17 catchments the Zhang curves underestimate the change in mean annual water yield in these small experimental catchments. This could be due to (i) vegetation age structure...
Chapter 6: Adjusting flow duration curves for changes in forest cover

(single age vs. mixed age forest), (ii) the range in forest cover used in the classification of catchments as by Zhang et al. (over 70% forest cover was assumed to be forested), and/or (iii) the spatial variability of rainfall and soil moisture across the larger catchments used by Zhang. These three factors, along with the climatic variation between the control and the treatment periods, may combine to result in the Zhang curves producing lower estimates of streamflow changes than are observed in the small experimental catchments. The impact of forest age structure on the mean annual streamflow can be seen by looking at forest response curves that show how forest age influences streamflow (Kuczera, 1987; Watson et al. 1999). They show that maximum evapotranspiration from forested catchments occurs around 20 years of growth for Mountain Ash (Eucalyptus Regnans) forest. Following approximately 20 years of age, ET reduces as the forest ages and thus, catchments with an even aged forest will have a lower ET (thus higher water yield) than rapidly growing even aged plantations. The classification of catchments with greater than 70% forest cover as forested will result in the generalised forest curve developed by Zhang et al. 2001 representing forest cover of between 70 and 100%. Thus, it does not necessarily provide the upper envelope as is assumed in this and other applications of the Zhang curves (Dawes et al. 2004; Herron et al. 2002). The spatial distribution of rainfall and soil properties across larger catchments will also influence the excess water available for runoff. In larger catchments there tends to be a mosaic of vegetation with heterogeneous geology, topography and soils. These factors combined with the spatially variable nature of rainfall may act to moderate the hydrological response in large catchments compared to smaller experimental catchments where rainfall, geology and soil are more uniform (Wilk et al. 2001).

The bucket model used to adjust the low flow portion of the FDC (the CTF or 95th percentile flow) aimed to provide a simple procedure to adjust the percentage of time flow occurs in a catchment. A bucket model was used as it allows the pattern of rainfall and potential evapotranspiration (PET) to be taken into account in the prediction. The results show that the simple bucket model does a satisfactory job of predicting the change in the CTF percentile. As one would anticipate, for such a simple bucket model aimed at fitting the low flow section of the time series, poor fits occur for the high flows, however, mass balance was achieved for all catchments. Adjusting the bucket for a change in land use (using the mass balance) relies on the assumption that adjusting $S_{ET}$ accounts for any changes in interception and soil properties following a change in vegetation cover. Thus, the amount of soil moisture when the soil is saturated does not change following a change in vegetation cover and the recession
constant remains the same. In reality, it is possible that the soil properties will change following a change in vegetation. However, it is thought that the impact of these changes is likely to be insignificant compared to the changes in rooting depth or plant available water storage.

The results presented in this chapter used different lengths of record, and the catchments did not always have stable vegetation during the calibration and new equilibrium periods. In some catchments, there was also a difference in the climatic conditions between the calibration and new equilibrium periods. The length of the calibration and new equilibrium periods varied between 3 and 10 years. In some catchments, Red Hill and Pine Creek, streamflow measurements started when the trees were established. Thus, the calibration period was taken as being during the early years of the plantations while the trees are in the early stages of development it is anticipated that they will still have some effect on the streamflow, but it will be minimal compared to the fully mature plantation.

6.6 Conclusions

Much of the previous work on the impact of afforestation on streamflow has concentrated on mean annual streamflow. It is generally accepted that increasing forest cover reduces mean annual streamflow and predictive tools are available for assessing the impact of forest cover changes on mean annual streamflow. However, it is recognised that there is a need to make predictions at shorter time scales, such as monthly and daily flows. These time scales are particularly important for water security and ecosystem assessments. Paired catchment studies provide reliable measured data for quantifying the impact of vegetation change on streamflow at different time scales and the development of a robust model to predict changes in flow regime following forest cover change can benefit from our understanding of the paired catchment data.

The response of the flow duration curve to afforestation is dependent on limiting conditions for evapotranspiration. In high rainfall areas, the response will be more uniform across all flows, while for lower rainfall areas (where evapotranspiration is water limited for some part of the year) there will be a greater relative impact in the low flow region of the FDC (Lane et al., 2005; Brown et al., 2005). Depending on the asset of interest (floodplain health, aquatic biology, water security), this differential impact can be important. In addition, perennial streams may become ephemeral (dry for part of the year). For example, Lane et al. (2005) identified a number of catchments where there was a change in the number of zero-flow days. This represents a major change
in stream characteristics. As a result, it is important that models are developed that allow these changes in streamflow to be predicted.

The methodology developed for adjusting the FDC for forest cover change showed the potential for predicting the effects of afforestation and deforestation on FDCs. The model has been developed and has been tested on small experimental catchments undergoing large percentage changes in vegetation cover. The method described in this chapter links the mean annual water balance model of Zhang et al. (2001) to a parameterisation of the FDC, thus allowing the shape of the FDC to be adjusted for a change in forest cover. Despite the simplicity of the methodology, it showed promising results for predicting the impact of vegetation cover change on flow duration curves. Like the tools for predicting the impact of vegetation on the mean annual water balance, the methodology to predict the FDC is for the change from one equilibrium state to another and does not consider the time delays associated with the establishment of a hydrologic equilibrium under different forest covers.

The method developed in this chapter to allow the FDC to be adjusted for the change in forest cover, allows a link to be made between predictions of changes to mean annual streamflow and shorter time scales. This has some major advantages as it potentially allows mean annual changes to be linked to a time series of daily flows. This time series can then form the inputs to water routing models (such as REALM (Diment, 1991) or IQQM (Simons et al., 1996)) for regulated systems, allowing an assessment of the impact on all river users. The FDC can be used to generate a new time series of flow, via either rainfall runoff models (e.g. Sacramento) calibrated to the FDC or a spatial interpolation method.
CHAPTER 7  Predicting the impact of forest cover change on water users at local and regional scales

Chapter 6 outlined a methodology to adjust a catchment’s FDC for change in forest cover and tested this with data from paired catchments. The results showed that the methodology could be used to adjust a FDC for change in forest cover. However, Chapter 6 did not demonstrate how this methodology could be used to increase our understanding of the impact of forest cover changes on water users. This chapter applies this methodology for two scenarios relating to possible changes in forest cover in the upper Murrumbidgee River Basin, Australia. The FDC adjustment methodology is applied to 14 sub-catchments. The adjusted FDC is then used to produce an adjusted streamflow time series. This adjusted time series is then used as input in the Integrated Quantity and Quality Model (IQQM) for the Murrumbidgee River to allow the impacts of possible forest cover changes on local and regional water users to be investigated.

This chapter has been published as “Predicting the impact of plantation forestry on water users at local and regional scales: An example for the Murrumbidgee River Basin, Australia” Forest Ecology and Management Volume 251, Issues 1-2, pages 82-93.

7.1 Introduction

Along with climate change, farm dams, groundwater extraction, bushfires and irrigation water management, afforestation has been identified as one of the six threats to the shared water resources in the Murray Darling Basin (MDB) of southeast Australia. (van Dijk et al. 2006). Initiatives such as the 2020 Vision (DPIE, 1997) are aimed at expanding tree plantations within Australia. While expansion of tree plantations has a number of economic, social and environmental benefits, substantial changes in forest cover may lead to decreased streamflow in the river systems of the MDB.

To assess the impact of forest cover changes on streamflow at both the local and regional scale, predictive methods are required that assess the impact of forest cover changes on total water yield and its temporal distribution. Zhang et al. (2001) developed a simple water balance model that predicts the effect of forest cover changes on mean annual streamflow. This model is based on analysing data from 250
world wide catchment studies and is generally applicable for looking at changes in forest cover. This model has proven to be robust and has been incorporated into tools such as BC2C (Biophysical Capacity to Change; Dawes et al. 2004) as a means to predict the effect of changes in forest cover on mean annual streamflow. However, to understand how changes in forest cover impact on downstream water users, the associated changes in streamflow need to be input to river planning models such as IQQM (Integrated Quantity and Quality Model, Simons et al., 1996) and REALM (REsource ALlocation Model, Perera, 2005). These models operate on daily and monthly time steps and consequently mean annual streamflow predictions are not sufficient and methods are required that allow assessments to be made at shorter time scales.

Work on linking hydrologic impacts of forest cover changes in upland areas with river systems models is limited. However, two examples can be found in Herron et al. (2002) and Zhang et al. (2003). Herron et al. assessed the impact of large scale afforestation and climate change on water allocation in the Macquarie River system, NSW, Australia. By adjusting the parameters of the Sacramento rainfall runoff model to mimic the effect of changing tree cover and potential climate change, new inflow time-series data were derived for the Macquarie IQQM. This allowed an assessment to be made of the impacts of both climate change and afforestation on downstream water users. Zhang et al. (2003) applied a similar process to the Goulburn-Broken catchments in Victoria, Australia to assess the impact of large scale afforestation on allocations by linking a mean annual water balance model, a tree growth model and flow duration curve (FDC) analysis to adjust flows into the system simulation model for the Goulburn-Murray Water supply system. Both these papers considered impacts of large scale plantations and assessed the results in terms of changes in mean annual flows.

This paper outlines how predicted changes in mean annual streamflow can be linked to a daily river planning model via the use of daily flow duration curves using the methodology outlined in Chapter 6 (Brown et al. 2006b). This methodology adjusts the catchment daily FDC for a change in forest cover based on a predicted change in mean annual streamflow. This allows the inflow time series to daily river planning models to be adjusted for changes in forest cover, thus allowing the impact on downstream water users (e.g. irrigators, environment) to be assessed. The Murrumbidgee catchment was chosen because of its relevance to the Water for a Healthy Country (WfHC) – Murray Uplands project. This paper assesses the potential
impacts of two plantation scenarios on streamflow at different spatial and temporal scales. This is achieved by:

1. Predicting the mean annual water yield change and its spatial distribution based on current vegetation cover and two afforestation scenarios.

2. Adjusting the daily flow time series to assess the impact of forest cover changes on flow distribution in the upland catchments.

3. Using the Murrumbidgee IQQM to assess the impacts of upland streamflow changes on downstream water users.

### 7.2 Catchment description

Extending from south of Cooma in south eastern Australia to Balranald in the west, the Murrumbidgee catchment covers an area of 84,000km² and the river flows for a distance of approximately 1,600km. It is the third longest river in the Murray-Darling Basin (Figure 7–1a). The climate in the catchment ranges from the alpine areas of Kosciusko National Park to the semi arid regions of the western Riverina. The river has been regulated by two major storages in the upper regions of the catchment, Burrinjuck Dam (near Yass) and Blowering Dam (near Tumut).

The area of interest to the WfHC – Murray Uplands project is the area upstream of Wagga Wagga and including Billabong Creek in the southwest (Figure 7–1b). This region has an area of approximately 38,000km², with a mean annual rainfall ranging from approximately 500 mm to 2500mm. It has been divided into sub-catchments based on those used by HydroTechnology (1995) to derive inflows to the Murrumbidgee IQQM. Table 7-1 provides a summary of gauging stations used to provide inflow data to the Murrumbidgee IQQM and the distribution of current forest cover based on Ritman (1995).
### Table 7-1: Gauging stations used to provide inflows to the Murrumbidgee IQQM modelling

<table>
<thead>
<tr>
<th>Station ID</th>
<th>Station Name</th>
<th>Catchment Area (km²)</th>
<th>Mean Annual rainfall (mm)</th>
<th>Current % forest cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>410025</td>
<td>Jugiong Creek at Jugiong (Inverlochie)</td>
<td>2150</td>
<td>704</td>
<td>3</td>
</tr>
<tr>
<td>410005</td>
<td>Murrumbidgee River at Narrandera (residual area, Wagga Wagga - Narrandera)</td>
<td>7461</td>
<td>546</td>
<td>4</td>
</tr>
<tr>
<td>410044</td>
<td>Muttama Creek at Coolac</td>
<td>1060</td>
<td>731</td>
<td>6</td>
</tr>
<tr>
<td>410103</td>
<td>Houlaghans Creek at Downside</td>
<td>1181</td>
<td>585</td>
<td>1</td>
</tr>
<tr>
<td>410045</td>
<td>Billabung Creek at Sunnyside</td>
<td>864</td>
<td>647</td>
<td>7</td>
</tr>
<tr>
<td>410004</td>
<td>Murrumbidgee River at Gundagai (residual area, Burrinjuck Dam – Gundagai)</td>
<td>1310</td>
<td>814</td>
<td>13</td>
</tr>
<tr>
<td>410131</td>
<td>Murrumbidgee River at Burrinjuck Dam - Storage Gauge</td>
<td>13123</td>
<td>872</td>
<td>45</td>
</tr>
<tr>
<td>410001</td>
<td>Murrumbidgee River at Wagga (residual area, Gundagai – Wagga Wagga)</td>
<td>1701</td>
<td>715</td>
<td>9</td>
</tr>
<tr>
<td>410038</td>
<td>Adjungbilly Creek at Darbalara</td>
<td>392</td>
<td>1181</td>
<td>50</td>
</tr>
<tr>
<td>410071</td>
<td>Brungle Creek at Red Hill</td>
<td>115</td>
<td>1050</td>
<td>19</td>
</tr>
<tr>
<td>410047</td>
<td>Tarcutta Creek at Old Borambola</td>
<td>1707</td>
<td>888</td>
<td>33</td>
</tr>
<tr>
<td>410039</td>
<td>Tumut River at Brungle Bridge (residual area, Blowering Dam – Brungle Bridge)</td>
<td>596</td>
<td>1020</td>
<td>26</td>
</tr>
<tr>
<td>410043</td>
<td>Hillas Creek at Mount Adrah</td>
<td>570</td>
<td>1018</td>
<td>36</td>
</tr>
<tr>
<td>410048</td>
<td>Kyeamba Creek at Ladysmith</td>
<td>540</td>
<td>713</td>
<td>8</td>
</tr>
<tr>
<td>410057</td>
<td>Goobarragandra River at Lacmalac</td>
<td>661</td>
<td>1327</td>
<td>94</td>
</tr>
<tr>
<td>410059</td>
<td>Gilmore Creek at Gilmore</td>
<td>235</td>
<td>1265</td>
<td>50</td>
</tr>
<tr>
<td>410061</td>
<td>Adelong Creek at Batlow Road</td>
<td>138</td>
<td>1235</td>
<td>37</td>
</tr>
<tr>
<td>410102</td>
<td>Tumut River at Blowering Dam - Storage Gauge</td>
<td>1615</td>
<td>1368</td>
<td>80</td>
</tr>
<tr>
<td>410091</td>
<td>Billabong Creek at Walbundrie</td>
<td>2581</td>
<td>702</td>
<td>12</td>
</tr>
</tbody>
</table>

1. Based on catchment boundaries used in the scenario modelling
Figure 7–1: Location of Murrumbidgee catchment (a) shows the location of the main towns and irrigation areas, and (b) shows sub-catchments considered in the Murray uplands project.
7.3 Methods and Data

The methods for this work can be summarised into three key steps. These are (i) developing scenarios for plantation expansion and determining changes in mean annual streamflow for each sub-catchment, (ii) adjusting daily FDC and inflow time series for each scenario, and (iii) applying the river-planning model with a base case and adjusted inflow time series for each scenario.

Figure 7–2 shows how these steps are related. The method and data used in each stage are described below. The development of the forest cover change scenarios and the changes in mean annual flow (step 1) were undertaken on grid cells, while steps 2 and 3 required the results to be aggregated to the sub-catchment scale.

7.3.1 Forest cover change scenarios and mean annual streamflow

7.3.2 Determining suitable areas for plantation expansion

To develop a realistic plantation scenario spatial data for rainfall, current vegetation, reserves, productivity of plantations, distance from processing mills and percentage of
woody vegetation was required. A map of total area suitable for plantations was developed by determining the 250m grid cells that are considered suitable in all of the decision layers. As it was unlikely that the entire suitable area would be planted, two scenarios were considered. Both scenarios simulated the planting of 30,000ha in the Uplands region of the Murrumbidgee catchment. 30,000ha was chosen as it was considered to be the upper limit of likely plantation expansion. To assess the envelope of responses for each scenario, two extremes were considered that relate to the location of the plantations and the plantation water use.

To determine the suitable areas in each decision layer the following rules were applied.

1. Rainfall must be greater than 500mm (Figure 7–3a)

2. Current vegetation is suitable if it is native shrublands and heathlands, native grassland and minimally modified pasture, perennial crops, annual crops and highly modified pasture, bare ground or unknown (Figure 7–3b).

3. Areas not reserved for other uses are considered suitable (Figure 7–3c; DEH, 2000).

4. Stem volume growth rate (productivity) of plantation greater than 18 m$^3$/ha/y. Productivity has been determined using ProMod and the lower limit of 18 m$^3$/ha/y is based on acceptable growth rates for plantations. (Figure 7–3d; Booth et al., 2002)

5. Area must be within an 80km radius of a pulp mill, used as an estimate of acceptable travel distance. Pulp mills are located at Tumut, Tumbarumba and Wagga Wagga. (Figure 7–3e; BRS, 2006)

6. Minimum of 1ha of non-woody vegetation in each 250m grid cell. This equates to the percentage of woody vegetation being less than 84%. 84% is the required threshold as the original woody vegetation grid (Ritman, 1995) was based on 25m grid cells. When scaled to 250m, 16% represents 16 x 25m of cells or 1ha within the 250m grid cell that are suitable for planting. (Figure 7–3f)
Figure 7-3 shows the suitable area in each of the decision layers, while Figure 7-4a shows the final areas considered suitable for plantations.

### 7.3.3 Determining changes in mean annual streamflow

For each grid cell considered suitable for plantation the change in mean annual streamflow was calculated using the mean annual water balance model developed by Zhang et al. (1999, 2001) for grass and forested conditions. This mean annual water balance model calculates mean annual actual evapotranspiration based on mean annual rainfall, and has been implemented in ArcInfo based on the characteristics of each cell as described in Zhang et al. (2003). Assuming that there is no net change in water storage, the mean annual water yield can be calculated as the difference between the mean annual rainfall and mean annual actual evapotranspiration. This allows the cells that have the highest and lowest impact on water yield to be determined. Figure 7-4 shows the linkages between the grids of suitable area, rainfall, and the mean annual water balance model to create a grid of water yield reduction.
Chapter 7: Impact of forest cover changes at local and regional scales

Figure 7–3: Areas considered suitable in each of the decision layers. (a) rainfall greater than 500mm, (b) current vegetation, (c) reserves, (d) productivity greater than 18 m$^3$/ha/y, (e) area within 80 km of wood processing mills and (f) woody vegetation less than 84% of area.
7.3.4 Determining scenario areas

In total, approximately 300,000ha was determined to be suitable for plantation expansion within the Uplands of the Murrumbidgee catchment. To determine the specific areas for each of the 30,000ha scenarios, areas that have the highest and lowest reduction (greatest and least impact) on water yield were determined. These
areas were determined by calculating the change in water yield for the areas available within each 250m grid cell that could be changed to plantation (i.e. if a grid cell (6.25ha) is 50% woody vegetation, then only 50% or 3.125ha can be changed to plantation). Figure 7–5 shows the areas for the High Water Yield Reduction (HWYR) Scenario and Low Water Yield Reduction (LWYR) Scenario.

Figure 7–5: Areas for plantation expansion considered in each scenario. The black areas indicate HWYR, while dark grey areas show the LWYR.

The changes in mean annual water yield were then aggregated by summing the results for each grid cell to the sub-catchment scale. This allows the FDC and daily flow time series at the outlet of each sub-catchment to be modified.

7.3.5 Adjusting FDCs and daily time series

To modify the daily flow time series, the method described in Chapter 6 and Brown et al. (2006b) was used to adjust the flow duration curve in each sub-catchment. This method uses the predicted change in mean annual water yield to adjust the FDC for a change in forest cover. It requires inputs of daily streamflow, daily rainfall, daily potential evapotranspiration (PET), current percentage forest cover, and the new percentage forest cover for each scenario.

Daily streamflow data for each sub-catchment were obtained from the New South Wales, Department of Natural Resources (DNR). The data had been extended using the Sacramento Rainfall Runoff model to allow the River Planning Model to be applied
from 1890 to 2005. Daily rainfall and PET data were obtained for each sub-catchment from the NRM enhanced meteorological data sets on the Silo Website (http://www.nrm.qld.gov.au/silo/). The grid location used to obtain rainfall and PET data for each sub-catchment was determined by calculating the mean annual rainfall and PET for each sub-catchment, and determining which grid cell within the sub-catchment contained close to the mean annual value. Daily data was then extracted for each of these cells, providing a time series from 1889 to 2005.

The FDC adjustment method is described in detail in Brown et al. (2006b) and involves the following steps. (1) Calculating the FDC for current forest cover; (2) parameterising the FDC based on the method used in Best et al. 2003b, and (3) adjusting the FDC parameters based on estimated change in mean annual water yield for the new forest. This leads to a new parameterised FDC for proposed plantation expansion in each sub-catchment.

To assess the impact of plantation expansion in the regulated Murrumbidgee River system, it is necessary to convert the predicted FDC under new forest cover to a time series of daily streamflow. This was done by combining the daily time series for current forest cover with the FDCs for current forest cover and proposed forest cover using the method outlined in Zhang et al. 2003. To assess the impacts in the ungauged residual catchments a simpler method was used where the existing residual inflows were factored according to the change in mean annual water yield.

### 7.3.6 Linking to river systems models

The aim of this study is to predict the impact of potential plantation expansion on local and regional water resources. In order to link the changes in upland areas to downstream, it is necessary to route the adjusted tributary streamflow through a river system model. IQQM is the river system model used in this study, and was developed by NSW DNR to represent the major hydrological and water management processes that occur in the river system using nodes and links. The model has been developed primarily for planning and policy development. IQQM is currently used within NSW in the development of environmental flow rules, assessment of inter-valley transfers, water trade and to resolve issues of water sharing between competing water users.

IQQM operates at a daily time step and is used to simulate river system flows over long periods (i.e. greater than 100 years). The Murrumbidgee IQQM was run over the period 1890 to 2005. This model incorporates catchment-specific rules for water allocation, irrigation diversion, inter-valley transfers and end-of-system flows. The
model routes water down the system subject to storage releases, tributary inflows, diversions and town water supplies, losses and environmental flow rules.

The major features of the regulated Murrumbidgee system are Burrinjuck and Blowering dams, three major irrigation areas (Murrumbidgee Irrigation Area (MIA), Coleambally Irrigation Area (CIA) and Lowbidgee), town water supplies, diversions to the Murray and wetlands (Figure 7–1a). To assess the impact of the proposed changes in forest cover, the scenario model runs of the Murrumbidgee IQQM need to be compared to a baseline. The 1993/94 Cap conditions have been used as the baseline for this paper. This model simulates the 1993/94 levels of development in line with the Murray Darling Basin Cap (MDBC, 2000). To derive the impact of the two scenarios on streamflow change in allocations, changes in streamflow at Wagga Wagga and Balranald, changes in total diversions (MIA + CIA + inter-valley transfers), and changes in Lowbidgee diversions are assessed at a mean annual scale and on an annual distribution. Changes are presented for a water year starting on 1st October and ending on 30th September.

7.4 Results

The results for each of the scenarios are presented in terms of changes in upland areas (mean annual flow and FDCs) and impacts on allocations, streamflow and diversions in the regulated river system. Changes in tributary flows (sub-catchments) have been presented as percentage reductions in mean annual streamflow, percentage reductions in the 5th, 10th, 30th, 50th, 70th, 90th, and 95th percentile flows and changes in the Cease To Flow (CTF) percentile. Changes in the regulated system are presented in terms of changes in mean annual and annual allocations, diversions and streamflow.

7.4.1 Local catchments

Table 7-2 shows the forest cover and percentage changes in mean annual streamflow in each of the Upland sub-catchments. Under current conditions, tributary inflow downstream of Burrinjuck and Blowering contribute approximately 1150 GL/year. Under the 30,000ha HWYR scenario total tributary inflows are reduced by approximately 50GL/year (4%) and under the 30,000ha LWYR scenario total tributary inflows are reduced by approximately 10 GL/year (1%). Changes in streamflow upstream of Burrinjuck and Blowering dams are 3 GL/year under the HWYR reduction scenario and 1 GL/year under the LWYR reduction scenario.
Table 7-2: Changes in forest cover and streamflow in upland sub-catchments of the Murrumbidgee River Basin (changes are shown in bold)

<table>
<thead>
<tr>
<th>Gauge Number</th>
<th>Gauge Name</th>
<th>Percentage Forest Cover</th>
<th>30,000 ha High</th>
<th>30,000 ha Low</th>
<th>30,000 ha High</th>
<th>30,000 ha Low</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Current</td>
<td>3.1</td>
<td>3.1</td>
<td>5.6</td>
<td>0.0% -1.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.2</td>
<td>6.2</td>
<td>9.9</td>
<td>0.0% -2.3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>0.0% 0.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7.4</td>
<td>7.4</td>
<td>7.7</td>
<td>0.0% -0.3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50.2</td>
<td>50.6</td>
<td>50.2</td>
<td>0.0% 0.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>18.7</td>
<td>26.8</td>
<td>18.7</td>
<td>-5.6% 0.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>32.8</td>
<td>36.0</td>
<td>32.8</td>
<td>-3.7% 0.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>36.2</td>
<td>44.8</td>
<td>36.2</td>
<td>-7.5% 0.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7.8</td>
<td>7.8</td>
<td>10.5</td>
<td>0.0% -1.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>93.7</td>
<td>95.4</td>
<td>93.7</td>
<td>-1.4% 0.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50.4</td>
<td>73.4</td>
<td>50.4</td>
<td>-15.8% 0.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>37.0</td>
<td>71.4</td>
<td>37.0</td>
<td>-23.3% 0.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12.1</td>
<td>12.1</td>
<td>13.6</td>
<td>0.0% -1.0%</td>
</tr>
</tbody>
</table>

|              |                                        |                         | 4.2            | 4.2           | 4.8           | 0.0% -0.6%    |
|              |                                        |                         | 13.0           | 13.5          | 18.7          | -0.6% -2.8%   |
|              |                                        |                         | 8.9            | 8.9           | 9.4           | 0.0% -0.3%    |
|              |                                        |                         | 26.3           | 30.9          | 26.3          | -3.7% 0.0%    |

|              |                                        |                         | 44.4           | 44.6          | 44.6          | -0.3% -0.1%   |
|              |                                        |                         | 79.9           | 80.7          | 79.9          | -0.5% 0.0%    |
|              |                                        |                         | 55.2           | 55.2          | 55.2          | 0.0% 0.0%     |

The mean annual changes in streamflow have differing impacts on high and low flows, and these changes can be summarised using the FDC. Table 7-3 and Table 7-4 show the changes at different percentile flow for each of the tributaries undergoing a change in forest cover for the HWYR and LWYR scenarios respectively. The results show that for the HWYR scenario, the low flows (90th and 95th percentiles) are reduced by proportionally larger amounts than the high flows. For the LWYR scenario, all catchments show an increase in the percentage of time flow is zero. Figure 7–6 provides an example of the change in the entire FDC for Adelong creek. The inset depicts the low flow section of curve, used to define daily extractions limits as described in “A guide to the water sharing plan for Adelong Creek Water source” (DIPNR, 2005). These results confirm that vegetation cover changes has the potential
to reduce the percentage of time that water can be extracted in each of the water access classes. This reduction of time will impact on the volume of water that may be extracted under the unregulated licence conditions, which may have significant impacts on water users.

Figure 7–6: Predicted change in Adelong creek FDC. The insert looking at the low flow section of the curve, show the four flow classes for the Adelong Creek water sources based on the Batlow Road gauge. Very low flows (< 12 ML/day), Class A refers to low flows (flows between 12 and 20 ML/day), Class B (medium flows - 20 and 30 ML/day), Class C (high flows > 30ML/day).
Table 7-3: Changes in percentile flows in tributary catchments (30,000ha HWYR scenario) and cease to flow (CTF) percentile under current and HWYR scenario.

<table>
<thead>
<tr>
<th>Gauge Number</th>
<th>Gauge Name</th>
<th>Percentage of time flow is equalled or exceeded</th>
<th>CTF percentile (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>410038</td>
<td>Adjungbilly Creek At Darbalara</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>410071</td>
<td>Brungle Creek At Red Hill</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>410047</td>
<td>Tarcutta Creek At Old Borambola</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>410043</td>
<td>Hillas Creek At Mount Adrah</td>
<td>7%</td>
<td>8%</td>
</tr>
<tr>
<td>410057</td>
<td>Goobarragandra River At Lacmalac</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>410059</td>
<td>Gilmore Creek At Gilmore</td>
<td>14%</td>
<td>14%</td>
</tr>
<tr>
<td>410061</td>
<td>Adelong Creek At Batlow Road</td>
<td>22%</td>
<td>22%</td>
</tr>
</tbody>
</table>

Table 7-4: Changes in percentile flow in tributary catchments (30,000ha LWYR scenario) and change in cease to flow (CTF) percentile. Note: Blanks indicate that there was no flow under baseline conditions.

<table>
<thead>
<tr>
<th>Gauge Number</th>
<th>Gauge Name</th>
<th>Percentage of time flow is equalled or exceeded</th>
<th>CTF percentile (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>410025</td>
<td>Jugiong Creek At Jugiong (Inverlockie)</td>
<td>0%</td>
<td>2%</td>
</tr>
<tr>
<td>410044</td>
<td>Muttama Creek At Coolac</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>410045</td>
<td>Billabung Creek At Sunnyside</td>
<td>0%</td>
<td>4%</td>
</tr>
<tr>
<td>410048</td>
<td>Kyeamba Creek At Ladysmith</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>410091</td>
<td>Billabong Creek At Walbundrie</td>
<td>1%</td>
<td>1%</td>
</tr>
</tbody>
</table>
7.4.2 Impacts on downstream water users

The reductions in streamflow due to changes in vegetation cover in the Uplands may affect downstream water users in the regulated system (irrigators, town water supplies, the environment and end-of-system flows). Table 7-5 provides details of the mean annual reduction in allocation, diversion and streamflow. Allocation levels on 1\textsuperscript{st} October have been used as this represents a typical decision date for planting of summer crops in the Murrumbidgee River system. On a mean annual basis the changes in allocations, total diversions, Lowbidgee diversions and streamflow at mid-system (Wagga Wagga) and end-of-system (Balranald) are small. However, to gain a full appreciation of the impacts, individual years and sequences of years need to be assessed. Figure 7–7, Figure 7–8 and Figure 7–9 show the spread in the change in allocation, change in streamflow and change in diversion for the climate sequence over which the model was applied.

<table>
<thead>
<tr>
<th></th>
<th>Mean annual reduction in allocations</th>
<th>Mean annual reduction in diversions</th>
<th>Mean annual reduction in streamflow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Allocations</td>
<td>Total Diversions</td>
<td>Lowbidgee</td>
</tr>
<tr>
<td>30,000ha high</td>
<td>0.7%</td>
<td>0.4%</td>
<td>0.05%</td>
</tr>
<tr>
<td>30,000ha low</td>
<td>0.2%</td>
<td>0.1%</td>
<td>0.03%</td>
</tr>
</tbody>
</table>

In the majority of years there is no change in allocations, with only 35 years of change in the HWYR scenario and 12 years in the LWYR scenario. The maximum absolute reduction in allocation in both scenarios is 2% on the 1\textsuperscript{st} of October. This equates to a maximum percentage reduction in allocation of 3.5% (Figure 7–7). In some years increases in allocation may occur, due to feedbacks from previous years, resulting in increases in the storage levels used to determine the level of allocation. The percentage of time 100% of allocation is available on the 1\textsuperscript{st} October reduces from 62% to 59% under the HWYR scenario and from 62% to 61% under the LWYR scenario.
Chapter 7: Impact of forest cover changes at local and regional scales

Figure 7–7: Box plot showing the spread in the change in allocations. Solid line shows the median, thin lines show the 25th and 75th percentiles and the whiskers show the spread. 30,000ha high and 30,000ha low indicate the HWYR and LWYR scenarios respectively.

Figure 7–8 shows the percentage reduction in streamflow at Wagga Wagga (mid-system flow) and at Balranald (end-of-system flow). The change in annual streamflow at Wagga Wagga ranges from an 184GL reduction to an 8GL increase for the HWYR scenario, and from a reduction of 50GL to an increase of 30GL in the LWYR scenario. The change in annual streamflow at Balranald ranges from a 90GL reduction to an 18GL increase for the HWYR scenario, and from a 33GL reduction to a 28GL increase for the LWYR scenario. The combination of decreasing and increasing flows depends on the feedbacks in the system. The maximum volume reductions do not indicate the critical years for irrigation, the maximum volume reductions occur in the wet years, while years that are potentially more critical for irrigation are the dry years. Thus, the percentage reduction in flow, as depicted in Figure 7–8, give a better indication of the impact in critical years as larger percentage reductions occur during the dry years. These results show the flow at Wagga Wagga is reduced by a maximum of 3.2% and 1.9% in the HWYR and LWYR scenarios respectively, while maximum reductions at Balranald are 18% and 16%.
Changes in diversions are presented in terms of total diversions and diversions to the Lowbidgee. On an annual basis changes in total diversions vary from a 141GL (10%) reduction to a 20 GL (1%) increase in both the HWYR and LWYR scenarios (Figure 7–9). The change in diversions indicates either a change in planted area or change in inter-valley transfers (IVT). Change in total planted area in the catchment account for changes in diversions in the majority of years. However, in the year of maximum diversions reduction (10%) the reduction is due to a reduction in inter-valley transfers. In the 1993/94 cap version of the Murrumbidgee IQQM model, the determination of the amount of water transferred from the Murrumbidgee to the Murray between the 28th February and 19th June is in part dependent on the level of allocation in mid October of the previous year. If allocation levels are below 60% on the 17th of October, transfers from the Murrumbidgee to the Murray are significantly reduced. In the case of the year of maximum reduction the base case allocation levels were 60% on the 17th of October, while for the two afforestation scenarios allocation levels were 58%. This has resulted in IVT being reduced from 115GL to 10GL. This reduction in IVT during this year has two impacts: (i) reduced flows into the Murray River; and (ii) increased dam storage that potentially influences allocations in subsequent years.

The change in annual diversions to the Lowbidgee area, range from a 56GL reduction to a 51GL increase for the HWYR scenario, and, from a 40GL reduction to a 34GL
increase for the LWYR scenario (Figure 7–9). The diversions to Lowbidgee are a combination of unregulated and regulated diversions. In both the HWYR and LWYR cases the unregulated diversions are always reduced. The rules associated with regulated diversions are extremely complex, being a function of unregulated flow to Lowbidgee, flow thresholds at Wagga and Maude Weir, volumes of water within Lowbidgee and time of the year. Generally these rules aim to maintain a consistent flow of surpluses to Lowbidgee. The consequence of this is that in the HWYR scenario there is only a 0.05% reduction in diversions to Lowbidgee. This in turn creates a much larger downstream impact at Balranald of 2.6% compared to the 1.2% at Wagga (Table 7-5). The reductions in diversions to Lowbidgee are attributed to a reduction in the amount of flow above a critical diversion threshold. The increases in diversions are attributed to higher thresholds that stop diversions to Lowbidgee that are no longer reached due to flow reductions in the HWYR and LWYR scenarios.

![Graph showing spread in annual reduction in diversions. Changes in total diversions refer to diversions to MIA, CIA, and inter-valley transfers. Changes in diversions to Lowbidgee refer to Lowbidgee flood control and irrigation district as shown of Figure 7–1a.]

**Figure 7–9:** Spread in annual reduction in diversions. Changes in total diversions refer to diversions to MIA, CIA, and inter-valley transfers. Changes in diversions to Lowbidgee refer to Lowbidgee flood control and irrigation district as shown of Figure 7–1a.

### 7.5 Discussion

The results presented in this paper show that on a mean annual basis the whole-of-catchment scale impacts of the two vegetation change scenarios on streamflows, allocations, and diversions are minimal. However, when local responses, critical years, and sequences of years are considered some potentially high impacts are identified. At the local scale, the results for Adelong Creek (Figure 7–6) show the potential to reduce low flows due to increasing the forest cover in the catchment from 37% to 71% of the land area. This, in turn, can be translated to the percentage of time unregulated
water users with water access licences could access the water under the current water-sharing plan (DIPNR, 2004). We estimate, that under the 30,000ha HWYR scenario, flow in the very low flow class would occur as much as 5% less often while flows in A and B classes occur as much as 10% less often than at present. While these impacts are minimal on the larger irrigation areas downstream (MIA, CIA) they have the potential to affect current water rights of local water users and should be considered when planning for future plantations. While changes at the local scale for the LWYR scenario would be less significant, tree plantation productivity in these catchments is also considerably lower.

At the regional scale, the impacts of both afforestation scenarios are small in most years. This is not surprising, as 30,000ha equates to approximately 0.4% of the total basin. While this area is entirely located in the flow contributing areas this still only accounts for a 1% change in land use in the area upstream of Wagga Wagga. In both scenarios most of these changes occur downstream of the two major dams, thus the impacts in the regulated system are buffered by dam releases. The results for the changes in streamflow, allocation and diversion, show that the major reductions are on diversions (with a maximum 10% reduction) and end-of-system flows (maximum of 18% reduction). Both of these impacts are felt outside the Murrumbidgee River system, with the reduction in flows at Balranald and the reduction in diversions (due to changes in IVT) reducing flow into the Murray. The reduction in IVT, illustrates the potential impacts of river operation rules that are based on threshold values. The results of the modelling show how the system is managed to buffer impacts on the users within the system, and consequently will transfer any negative impacts to outside the system where possible.

The modelling of plantation expansion did not consider a number of issues that will influence water use in the catchment. These include:

1. the location of the plantation within the sub catchment;

2. the species planted; and,

3. the impact of plantation age, rotation length, thinning and staged plantings.

The location of planting in the catchment has only been considered in terms of rainfall gradient, with plantings in high rainfall areas having a larger impact on streamflow than plantings in low rainfall areas (Zhang et al. 2001). Classical forest hydrology literature suggests that the reduction in streamflow is linearly proportional to fraction of the
catchment planted (Bosch and Hewlett, 1982). However, it is more likely that the further you plant from the stream the smaller the impact on streamflow. Vertessy et al. (2003) presented results supporting this idea from numerical modelling experiments using Topog (Vertessy et al. 1996). The results show that the impact of planting the top 20% of a catchment has a much smaller impact than planting the bottom 20%, assuming that the rainfall is the same over the entire catchment. This is due to trees closer to streams having a greater opportunity to intercept water. In order to adequately assess the impact of plantation location on streamflow a more process-based, distributed modelling approach would be required than that applied in predicting the changes in these catchments. Different tools are available to assess the spatial impact of reforestation on water resources and salinity (van Dijk, 2007). These include, BC2C (Dawes et al., 2004), CATSALT (Tuteja et al. 2003), 2CSalt (Stenson et al., 2005), and the Framework for Land Use and Hydrology modelling (FLUSH; Gallant et al., 2005). In reviewing these different tools, van Dijk (2007) concluded that this generation of modelling tools are sufficient to assess the spatial impact of reforestation on streamflow and stream salinity at different scales.

Species type for both trees and crops (e.g. annual vs. perennial pastures) are likely to impact on ET and therefore the amount of water in the streams. This study made no distinction between different tree or grass species and does not consider planting type and management. In reality, different species of trees or pastures will transpire different amounts of water depending on the site characteristics and suitability for the particular species. However, species types and plantation management are likely to have a second order impact when compared to the difference between the two broad categories used in this paper.

Plantation age, rotation length and establishment period (staged plantings) will all influence transpiration rates and hence the maximum reduction in streamflow. Investigations in the impact of age on water yield indicate that when converting grass to forest, maximum impact will not be felt until 10 – 20 years of age (Brown et al. 2005). Hence, the impact on streamflow will be less at the beginning of rotation than at the end of the rotation and different combinations of tree ages in the catchment will affect the overall hydrological response. If the establishment of plantations in the catchment is staggered, then a catchment will contain trees of varying ages and thus not exhibit the maximal reductions of single age plantations. However, how you incorporate the forest age related factors, with climatic variability in the models used in this paper requires further investigation so that the combined effect of climate and
vegetation can be considered. A recent study suggested that climate change may lead to reductions in streamflow for catchments in the MDB with 6 to 15% reduction in mean annual streamflow predicted for the Murrumbidgee (Austin et al., 2006).

While plantations can present significant environmental benefits, their impact on streamflow needs to be recognised (Brown et al., 2005, Zhang et al., 2006). It is essential that this information be incorporated into the development of water resources management strategies. This study demonstrated that the impact of plantations on water resources could be estimated by linking catchment water balance models with river planning models. This way it enables us to express the impacts in terms of changes in water allocation and diversion, which are directly relevant to water resources management. The approach developed in this study has the potential to be applied to other catchments in Australia and elsewhere for estimating plantation impacts on water security.

7.6 Conclusions

This paper has evaluated the impact of potential plantation expansion in the Murrumbidgee River Basin on streamflow and water use in both sub-catchments and at the regional scale by linking uplands models to whole-of-system river planning models. The linking of the mean annual water balance model, the FDC adjustment method and IQQM has illustrated the advantage of value adding to river planning models that are used for policy development, auditing, and operations by government agencies. The combining of models allows the whole-of-system response to be assessed and allows the conversion of yield volume impacts in upland areas into changes in allocations and diversions in the downstream regulated system.

The two scenarios presented in this paper illustrate the potential to have significantly different impacts depending on the plantation location. These impacts differ at both the local and regional scale, with the results for Adelong Creek highlighting the need to assess both local impacts and whole-of-system response. The comparison of mean annual response and the distribution of annual responses shows the need to look at critical years and sequences of dry years as these years are likely to have the most significant impact on downstream water uses. These changes appear to come primarily from the triggering of management rules that are based on threshold values. This can result in small changes upstream having big impacts for downstream water users including those outside the Murrumbidgee River system.
CHAPTER 8  Summary and Conclusions

8.1 Introduction
This thesis has outlined the development of a methodology to predict how a catchment’s FDC will change following a permanent change in forest cover. The work in developing and testing this methodology can be broken into four main pieces of work. These are:

1. the review of paired catchment studies (Chapter 2);
2. a consistent analysis of paired catchment data to assess annual changes in streamflow and changes to a catchment FDC (Chapter 4);
3. the development and testing of a method to predict the change in a catchment’s FDC following (Chapters 5 and 6); and
4. the application of the FDC adjustment methodology to sub catchments of the Murrumbidgee River Basin to allow the impact of possible forest cover changes on both local and regional water users to be assessed (Chapter 7).

This chapter summaries the work undertaken in this thesis, then discusses some of the limitations and future research needs.

8.2 Summary
Paired catchment studies have been widely used as a means of determining the magnitude of water yield changes resulting from changes in vegetation. The literature review presented in Chapter 2 focused on the use of paired catchment studies for determining the changes in water yield at various time scales resulting from permanent changes in vegetation. The review considered long-term annual changes, adjustment time scales, the seasonal pattern of streamflow and changes in both annual and seasonal flow duration curves. The paired catchment studies reported in the literature have been divided into four broad categories: afforestation experiments, deforestation experiments, regrowth experiments and forest conversion experiments. Comparisons between paired catchment results and a mean annual water balance model of Zhang et al. (2001) are presented and show good agreement between the two methodologies. The results highlighted the potential underestimation of water yield changes if regrowth experiments are used to predict the likely impact of permanent alterations to a catchment’s vegetation. An analysis of annual water yield changes from afforestation, deforestation and regrowth experiments demonstrates that the time taken to reach a
Chapter 8: Summary and Conclusions

new equilibrium under permanent land use change varies considerably, with deforestation experiments reaching a new equilibrium more quickly than afforestation experiments. The review of papers reporting seasonal changes in water yield highlights the proportionally larger impact on low flows while the comparison of flow duration curves provided a potential means of gaining a greater understanding of the impact of vegetation on the distribution of daily flows.

Chapter 2 highlighted that the effect of forest cover changes on mean annual streamflow is well understood with worldwide data having shown that increasing forest cover decreases the total volume of streamflow at the catchment scale. However, this chapter also highlighted that due to the different methods used to assess the impact of forest cover at the annual and sub-annual timescales, general conclusions can be difficult to draw. In Chapter 4 consistent methods of analysing paired catchment data was used to assess the impact of forest cover change in afforestation, deforestation, forest conversion and regrowth experiments on annual streamflow and flow duration curves. The annual analysis illustrated the different responses seen in the different experiment types. The results indicated that it takes between 8 and 25 years for a catchment to reach a new equilibrium following a permanent change in forest cover for afforestation or deforestation experiments. The results for the regrowth and forest conversion experiments show that it is not possible to use these studies to illustrate how permanent change in forest cover will influence streamflow. The results from regrowth and forest conversion experiments indicated that increases in streamflow last for between 3 years and the end of the period of record. However, in the majority of catchments the increase persisted for between 3 and 10 years. Analysis of the FDCs in the afforestation and deforestation experiments showed three different types of responses that could be group as:

1. catchments with changes in the percentage of time flow occur,
2. catchments with proportionally larger reductions in low flows compared to high flow, and,
3. catchments with a uniform reduction in all flows.

Chapters 2 and 4 both demonstrated that broad scale vegetation changes within a catchment are likely to lead to changes in water yield and flow regime. Following on from this analysis, Chapter 5 concentrated on developing a model (parameterisation) to describe the shape of any FDC. The FDC represents the relationship between the
magnitude and frequency of streamflow 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. In developing the parameterisation, it was recognised that 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. Therefore, in developing the parameterisation, the ability to use it to predict change was considered. Chapter 5 compared three models for describing FDCs under different forest covers and assessed how the model parameters change when forest cover is altered. The three models considered in Chapter 5 have different levels of complexity, but all have two common parameters, the proportion of zero flow days, and the median streamflow of the non-zero flow days. The models differed in the type of curve that is fitted to the normalised FDC when plotted in lognormal space. Data from the forty-seven paired catchment studies described in Chapter 3 were used in the analysis. These catchments, covering a wide range of climatic, vegetation and soil conditions, were used to evaluate the ability of the models to describe the shape of any FDC. The results indicated that under altered land use conditions the major changes occur in the parameters common to all three models, with the most complex model providing the most accurate description of the FDC in terms of matching total streamflow volume and individual percentiles.

In order to consider the impacts of forest cover change on water security, salinity, and environmental flows, methodologies are required that allow streamflow changes to be predicted. As outlined in Chapters 2 and 4, significant progress has been made in the ability to predict the impact of forest cover change on streamflow at the mean annual time scale. However, the ability to predict the impact of forest cover change on streamflow at shorter timescale is limited. Chapter 6 addressed this knowledge gap by developing a methodology to predict changes in a daily FDC following a change in forest cover. The methodology used a five-parameter model developed in Chapter 5, to describe the shape of the observed FDC for current vegetation conditions. To predict the changes in the FDC under altered forest cover, the parameters of the FDC model are adjusted based on an estimated change in mean annual streamflow. The linkage between the estimated change in mean annual streamflow and the parameters of the FDC model comes from the knowledge that the area under the FDC must be equal to the mean annual streamflow. This approach was tested on 17 small experimental catchments that had undergone large percentage changes in forest cover. The results presented in Chapter 6 showed the procedure developed is robust.
and can be used to predict changes in a catchment’s FDC following forest cover change.

With a robust method developed to adjust a catchment’s FDC for forest cover change, Chapter 7 aimed to illustrate the application this methodology by using a case study of catchments in the upland areas the Murrumbidgee River Basin. This allowed the assessment of potential impacts of forest cover changes on river water users at both the local and regional scale. This required the FDC adjustment model developed in Chapter 6 to be applied in unregulated areas of the catchment and then be linked to river planning models for regulated river systems. Chapter 7 illustrated how the model developed in Chapter 6 can be linked to the Integrated Quantity and Quality Model (IQQM) for the Murrumbidgee River system in southeastern Australia. Linking the two models allowed the impact of potential plantation expansion to be assessed at various points throughout the larger river system and allowed changes in streamflow in upland areas to be converted into impacts on allocations and diversion for downstream water users. To derive an envelope of responses, two plausible plantation expansion scenarios were considered. These were the planting of 30,000ha in areas that will have the largest reduction in mean annual water yield, and the planting of 30,000ha in areas that will have the smallest reduction in mean annual water yield. Chapter 7 showed that, at the regional scale, the impacts of these plantation scenarios are small on a mean annual basis, with reductions on allocations, diversions and end-of-system flows being 0.7%, 0.4% and 2.6% respectively for the maximum impact scenario. However, when there is a large increase in the area of plantations in one sub-catchment, the local scale mean annual streamflow reductions can be significantly higher (up to 23% reduction for the modelled scenarios), with larger percentage reductions seen in low flows than in the higher flows. Analysis of the annual impacts in the regulated system highlights the importance of looking at sequences of years and impacts in critical years with maximum annual reductions in allocations, diversions and end–of-system flows of 3.5%, 10% and 18% respectively for the maximum-impact water yield scenario. Linking the FDC model to a River Systems model has given an insight into how management rules that control the regulated system can be triggered. This triggering of rules can result in small changes in upland area having large impacts downstream if key threshold values are affected. These impacts have the potential to be felt not only in the Murrumbidgee River system, but also outside in the Murray River system.
8.3 Limitations and Future Research Needs

The results presented and discussed in the previous chapters of this thesis have lead to the development of a model that allows a catchment’s FDC to be adjusted for a change in forest cover, using a “top-down” modelling approach. The model development focused on the use of paired catchments studies to understand how changes in forest cover impact on streamflow. This understanding was then used to develop a methodology to link predictions of changes in mean annual water yield to the shape of the FDC when a permanent change in forest cover occurs. The methodology outlined and tested in the thesis has proven to be robust given good estimates of the change in mean annual stream flow. These FDC predictions could be improved by the development of new methodologies to improve the estimation of the change in mean annual streamflow following change in forest cover. There are a number of other issues associated with forest cover change that have not been addressed in this thesis, these include:

- How the distribution of forest cover across a catchment affects streamflow response.
- How vegetation age influences streamflow response and how staggered changes in forest cover impact on the magnitude the timing of the response.
- How the daily streamflow time series changes following a change in forest cover.

The following sections discuss the above points in relation to the results presented in this thesis and outlines how each of these limitations might be addressed.

8.3.1 Distribution of vegetation change across a catchment

The paired catchment studies used in this thesis have undergone large percentage changes in forest cover. These changes have in general been spread evenly across the catchment. In non-experimental catchments, these large percentage changes in forest cover are unlikely and thus it is important to consider where in the landscape the changes in forest cover occur. The location of the changes will affect the streamflow response and the time it takes for a catchment to respond to changes in forest cover.

There are a number of factors relating to the location of vegetation changes and streamflow. These include the variation in rainfall across the catchment and the distance of the vegetation change from the stream. The mean annual water balance...
model of Zhang et al. (1999, 2001) tells us that the impact of changing vegetation in high rainfall areas is greater than in low rainfall areas. Thus, if high rainfall areas of a catchment are planted, it may be anticipated that there will be greater reduction in streamflow than if low rainfall areas are planted. To account for this spatial variability in mean annual rainfall, the Zhang curves have been implemented in a GIS framework (Bradford et al., 2001 and Zhang et al., 2003). The approach taken by Bradford et al. used average rainfall and forest cover values across each sub-catchment. Therefore, this method does not account for the spatial distribution of rainfall within the sub-catchment. The approach taken by Zhang et al. (2003) uses a ‘cell’ based methodology similar to Vertessy and Bessard (1999). The use of a cell-based approach allows for a spatial variability in rainfall and vegetation across the catchment to be accounted for thus allowing for greater changes in streamflow if changes in forest cover occur in high rainfall areas compared to low rainfall areas. This cell based methodology implementation was used in the application of the Zhang curves in Chapter 7.

The other impact of distribution on the changes in streamflow is the distance the change in forest cover is from the stream and the proportion of the catchment treated. The general approach used to adjust for proportional changes in land use within a catchment is to assume a linear response (Bosch and Hewlett, 1982; Stednick, 1996) and this is the approach that has been taken in this thesis. It assumes that regardless of the location of the change the effect is the same for the same rainfall. There is very little data available to assess the impact of the location of vegetation change on catchment water balance. However, process understanding would imply that the closer the change occurs to the stream the greater the impact for the same rainfall. This is due to the fact that trees located near the stream have greater opportunity to intercept water compared to trees higher in a catchment. This idea was explored by Vertessy et al. (2003) where a numerical model, Topog (Vertessy et al. 1996), was used to predict the impact of planting a catchment from the bottom in increments of 10% compared to planting a catchment from the top. The results indicated the potential impact of tree planting led to a much greater reduction in runoff if the bottom 20-40 percent of the catchment is planted compared to the upper 20 – 40 percent. The mitigating factor to these results is site suitability. In some catchments, the areas adjacent to streams may not be suitable to planting due to shallow water tables. The response to afforestation in the Red Hill catchment is an example of this, where as due to intolerance of *Pinus radiata* to shallow water tables, tree planted near major drainage lines died leaving only 78% of the catchment afforested (Hickel, 2001).
In addition to the impact of vegetation distribution on the mean annual streamflow, the location of changes may also affect the time it takes for a catchment to respond. The results from the deforestation experiments presented in Chapter 4, showed us that the catchments that underwent changes evenly spread over the entire catchment (Don and Wight) responded more rapidly than catchments in which the change occurs in half of the catchment (Lemon). While these results may only hold in the Western Australian catchments, they may indicate that the location of planting may influence both the magnitude of the streamflow changes and also the timing of the response. While the Lemon and Don catchments both underwent similar changes in forest cover, the Don catchment was strip and parkland cleared, while in the Lemon catchment the bottom section of the catchment was cleared and they showed markedly different responses in streamflow.

It would also be expected that the location of the vegetation change in relation to the stream would affect the shape of the FDC. If planting occurs close to the stream, it would be anticipated that the impact on low flows would be more pronounced. This is because trees have a greater chance in intercept the baseflow component of the streamflow compared to trees located at higher elevations in the catchment. Again, there is little data available to support this assertion and it is an area that requires further research to improve our understanding of how the location of plantings affect the FDC.

8.3.2 Forest age impact on streamflow

This thesis has highlighted the difficulty in separating out the impact of vegetation from the impact of climate on streamflow. Not only is the climate and climatic variability likely to play a role in the pattern and nature of a catchment’s streamflow, but also on how rapidly a catchment responds to a change in land use. The ability of vegetation to extract water from the soil moisture stores, and how and when these stores are emptied and replenished impacts on the time taken for a catchment to reach a new equilibrium. In the case of afforestation, a dry year early in the rotation will speed up the reduction in streamflow, particularly low flows, as discussed in Chapter 4. However, there are other impacts of vegetation age that should be considered when dealing with the timing of streamflow responses. These are the age structure of the forests or plantations, and in the case of plantation, the length of rotation. This discussion about the vegetation impacts is focused around the establishment of plantation forestry on what would have previously been cleared agricultural land.

In non-experimental catchments, changes in land use, such as the establishment of plantations are not likely to happen instantaneously. It is more likely that changes in
forest cover will happen incrementally over a number of years. This may result in forested catchments having trees of various ages. The results presented in Chapter 4 show the impact of vegetation age on catchment response in terms of timing and magnitude. However, if a catchment contains vegetation of different ages then the timing and magnitude of the changes will be affected.

Brown et al. (2006a) developed a model that allows the impact of uptake and rotation length on the streamflow to be predicted using a grid cell approach across a catchment. Generalised response curves were developed based on a small set of paired catchment studies and these were used to assess how mean annual streamflow changes with time. Figure 8–1 shows the impact of different rates of uptake (the number of years over which a change in streamflow occurs) and different rotation lengths on the age structure when a catchment is converted from 100% grass/pasture to 100% plantation. Figure 8–2 shows the corresponding response in streamflow based on the response curves developed by Brown et al. (2006a). These figures highlight the impact different age structures can have on the streamflow response. The generalised response curves developed by Brown et al. do not take into consideration the difference in response between first and subsequent rotations. Work in the Glenmorgan experimental catchments in India has shown that the second rotation may have a more significant impact on streamflow than the first rotation (Sharda et al., 1998). The curves developed by Brown et al. (2006a) also assume when a plantation is harvested it returns to pre-treatment streamflow levels immediately. This assumption is reasonable given the little data available to assess the impact of second rotation plantings. However, the results of the deforestation experiments in Chapter 4 show that while there is an increase in streamflow if takes more than a single year to return to pre-treatment conditions. This makes the impact of subsequent rotations on streamflow an area that requires further research and experimental studies.
Figure 8–1: Affects of different rotation lengths and periods of uptake (or change) on age distribution in areas converted from 100% grass/agriculture to 100% forest. (From Brown et al. 2006a)

Figure 8–2: Impact of different rotation lengths and periods of uptake on predicted streamflow. (From Brown et al. 2006a)

8.3.3 Linking the FDC to the flow time series

The methodology presented in Chapter 6 provides a means of adjusting a FDC based on daily flow data for a change in forest cover. However, to make this tool more useful
to water resources management, a methodology is required that allows the FDC to be converted back into a time series of flows. This is required so that the results can be used as inputs into river systems models that are run on a daily or monthly time-step (Zhang et al. 2003). The conversion of the FDC to a time series can occur in a number of ways depending on the nature of the stream. If the catchment has the same or more streamflow days prior to change in forest cover then after the change, the method used by Smakhtin (1999) can be used to convert one time series to another. This method has been adopted in Chapter 7. Each flow in the original time series is assigned a percentile flow, then it is replaced with the flow from the predicted FDC that has the same percentile, thereby resulting in a predicted time series. This method assumes that there is no change in the pattern of streamflow. This method does not work if a catchment has a decrease in the number of zero flow days, as it is not possible to map zero flow days to days on which flow occurs. An alternate method for generating a time series of flows from a FDC is to use a rainfall runoff model. Rainfall runoff models can be calibrated to a FDC and thus used to generate a flow time series. However, further research should be undertaken into developing a methodology that expands on that of Smakhtin (1999) to allow mapping of zero flow day to days on which flow occurs.

8.4 Conclusions
Using data from paired catchment studies this thesis has investigated how forest cover changes impact on annual streamflow and flow duration curves. Following this investigation, a robust methodology for adjusting a catchment’s FDC for a change in forest cover has been developed. In undertaking this work, the following conclusions were drawn:

1. A comparison of paired catchment studies and the mean annual water balance model of Zhang et al. (2001) indicated good agreement between the observed results in the paired catchments and the mean annual water balance approach.

2. The transient nature of the water yield changes makes the use of regrowth experiments for predicting the impacts of permanent vegetation changes on water yield unreliable.

3. Catchments with uniform rainfall across difference seasons tended to show more uniform reductions in water yield across all seasons.
4. Analysis of the FDCs in afforestation and deforestation experiments showed that three types of response could be observed. These are: (i) a change in the percentage of time flow occurs, (ii) a proportionally larger reduction in low flows compared to high flow, and (iii) a uniform proportional change in all flows.

5. Of three potential models considered, a five-parameter model gives the best fit to observed FDCs, and following forest cover change the major parameter changes occur in the parameters relating to the median flow and the proportion of zero flow days.

6. Response of the flow duration curve to afforestation is dependent on limiting conditions for evapotranspiration. In high rainfall areas, the response will be uniform across all flows; while for lower rainfall areas (where evapotranspiration is water limited for some part of the year), there will be a greater relative impact in the low flow region of the FDC.

7. It is possible to develop a simple methodology for linking the mean annual water balance model of Zhang et al. (2001) to a parameterisation of the FDC to predict the impact of forest cover change on a catchment FDC.

8. The linking of the mean annual water balance model, the FDC adjustment method and IQQM has allows the whole-of-system response to be assessed and allows the conversion of streamflow reductions in upland areas into changes in allocations and diversions in the downstream regulated system.
References


Blackie, J.R., 1979. Summary of results of the Kericho experiments Hydrological changes as a result of conversion of forest to tea plantation, Kenya. East African Agricultural and Forestry Journal 43, 139–140.


Brown, A., Hairsine, P., Freebairn, A. 2006a. The development of the Tasmanian Land Use Change and Streamflow (TasLUCaS) tool. CSIRO Land and Water Science Report 54/06. Canberra: CSIRO.


BRS, 2006. Spatial data for forest industry processing sites in the Murray Darling Basin, National Forest Inventory Dataset, Bureau of Rural Sciences, Canberra.


References


Department of Infrastructure, Planning and Natural Resources (DIPNR), 2005. A guide to the water sharing plan for Adelong Creek water source. Publication No: 05_029

Department of Infrastructure, Planning and Natural Resources (DIPNR), 2004. A guide to the water sharing plan for the Murrumbidgee Regulated River water source. Publication No. 04_194.


References


References


References


References


References

allocation: an example for the Goulburn-Broken catchments Cooperative Research Centre for Catchment Hydrology Report No 03/05, Monash University, Victoria, Australia.

# Appendix A: Details of additional catchments used in Literature Review

<table>
<thead>
<tr>
<th>Treated Catchment</th>
<th>Control Catchment</th>
<th>Source of info</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Karuah, NSW, Australia</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barratta</td>
<td>1577 588</td>
<td>Logging without regeneration burn 1976-1983</td>
</tr>
<tr>
<td>Bollygum</td>
<td>1499 500</td>
<td>Logging without regeneration burn 1976-1983</td>
</tr>
<tr>
<td>Coachwood</td>
<td>1444 373</td>
<td>Plantation established after tractor clearing</td>
</tr>
<tr>
<td>Jackwood</td>
<td>1368 313</td>
<td>Loggin plus regeneration burn 1976-1983</td>
</tr>
<tr>
<td>Kokata</td>
<td>1562 518</td>
<td>Plantation established after tractor clearing 1976-1983</td>
</tr>
<tr>
<td><strong>Lidsdale, NSW, Australia</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L-6</td>
<td>14.7/25.3</td>
<td>Feb 1978 100% cleared and windrowed, and then burnt in April 1978. During winter 1978 catchment was planted with P. radiata.</td>
</tr>
<tr>
<td><strong>Tantawangalo Creek, NSW, Australia</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Willbob</td>
<td>755 100% cleared and windrowed, and then burnt in April 1978. During winter 1978 catchment was planted with P. radiata.</td>
<td>Lane and Mackay (2001)</td>
</tr>
<tr>
<td>Wicksend</td>
<td>1100 21.7</td>
<td>30% of area logged 1986-1989</td>
</tr>
<tr>
<td><strong>Tumut, NSW, Australia</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Redhill</td>
<td>876 135</td>
<td>38% of area logged 1986-1989</td>
</tr>
<tr>
<td><strong>Yambula State Forest, NSW, Australia</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geebung Creek</td>
<td>900</td>
<td>50ha afforested in 1988 and the remaining area (145ha) afforested in 1989</td>
</tr>
<tr>
<td>Peppermint Creek</td>
<td>75.9</td>
<td>None Hickel (2001)</td>
</tr>
<tr>
<td>Catchment</td>
<td>Area (ha)</td>
<td>Slope (%)</td>
</tr>
<tr>
<td>----------------</td>
<td>-----------</td>
<td>-----------</td>
</tr>
<tr>
<td>Grevillea Creek</td>
<td>92.5</td>
<td></td>
</tr>
<tr>
<td>Stringybark Creek</td>
<td>140</td>
<td>230-476</td>
</tr>
<tr>
<td>Germans Creek</td>
<td>225.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wyvuri experimental catchments, Babinda, Queensland, Australia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Creek</td>
<td>18.3</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brigalow Research Station, Queensland, Australia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>11.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cropper Creek, Victoria, Australia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clem Creek</td>
<td>46.4</td>
<td>E</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Maroojah experimental Area, Victoria, Australia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black Spur 1</td>
<td>17</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black Spur 2</td>
<td>9.6</td>
<td>14.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black Spur 3</td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ettercon 1</td>
<td>11.67</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treated Catchment</td>
<td>Control Catchment</td>
<td></td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------------</td>
<td></td>
</tr>
<tr>
<td><strong>Catchment</strong></td>
<td><strong>Area (ha)</strong></td>
<td><strong>Slope (%)</strong></td>
</tr>
<tr>
<td>Ettercon 4</td>
<td>9.03</td>
<td>Regrowth</td>
</tr>
<tr>
<td>Monda 1</td>
<td>6.31</td>
<td>Regrowth</td>
</tr>
<tr>
<td>Monda 2</td>
<td>3.98</td>
<td>Regrowth</td>
</tr>
<tr>
<td>Monda 3</td>
<td>7.25</td>
<td>Regrowth</td>
</tr>
<tr>
<td>Myrtle 2</td>
<td>30.8</td>
<td>Regrowth</td>
</tr>
<tr>
<td>Piccaninny</td>
<td>52.8</td>
<td>S</td>
</tr>
</tbody>
</table>

**Stewarts Creek, Victoria, Australia**
<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Slope (%)</th>
<th>Mean Elevation (m)</th>
<th>Aspect</th>
<th>Climate</th>
<th>Pre Treatment Vegetation</th>
<th>Post Treatment Vegetation</th>
<th>Mean Annual Rainfall (mm)</th>
<th>Mean Annual Streamflow (mm)</th>
<th>Catchment Control</th>
<th>Area (ha)</th>
<th>Slope (%)</th>
<th>Mean Elevation (m)</th>
<th>Aspect</th>
<th>Climate</th>
<th>Mean Annual Rainfall (mm)</th>
<th>Mean Annual Streamflow (mm)</th>
<th>Treatment</th>
<th>Calibration period</th>
<th>Source of info</th>
</tr>
</thead>
</table>

**Parwan Experimental Area, Victoria, Australia**

| Parwan 1 | 1.6 | N | Native Pasture woodland | 538 | Parwan 3 | 1.6 | N | 538 |
| Parwan 2 | 1.6 | N | Mediterranean type climate | Native Pasture improved pasture | 538 | Parwan 3 | 1.6 | N | 538 |
| Parwan 4 | 1.6 | S | Native Pasture woodland | 538 | Parwan 5 | 1.6 | S | 538 |
| Parwan 5 | 1.6 | S | Native Pasture improved pasture | 538 | Parwan 5 | 1.6 | S | 538 |

**Reefton Experimental Area, Victoria, Australia**

| Reefton 1 | 70.4 | 6 | 559 | N | Mediterranean Type climate | Native Eucalypt forest Regrowth | 1233 | 180 | 95.1 | 107. | 596 | NW | 1265 | 209 |
| Reefton 2 | 76.1 | 12 | 588 | W | Mediterranean Type climate | Native Eucalypt forest Regrowth | 1250 | 258 | 521. | 2 | 651 | S | 1440 | 318 |

**Collie River Basin, Western Australia**

| Dons | Mediterranean climate | Eucalypt Forest | Agriculture | 720 | Ernie | 270 | 720 |

*Appendix A*
<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Slope (%)</th>
<th>Mean Elevation (m)</th>
<th>Aspect</th>
<th>Climate</th>
<th>Pre Treatment Vegetation</th>
<th>Post Treatment Vegetation</th>
<th>Mean Annual Rainfall (mm)</th>
<th>Mean Annual Streamflow (mm)</th>
<th>Catchment Control Catchment</th>
<th>Area (ha)</th>
<th>Slope (%)</th>
<th>Mean Elevation (m)</th>
<th>Control Aspect</th>
<th>Source of info</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lemons</td>
<td>344</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ruprecht and Schofield (1991a)</td>
</tr>
<tr>
<td>Wrights</td>
<td>94</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ruprecht and Schofield (1989)</td>
</tr>
<tr>
<td>Balingup Brook Tributary</td>
<td>93.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Borg et al. (1988)</td>
</tr>
<tr>
<td>March Road</td>
<td>261</td>
<td>170-230m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>April Road North</td>
<td>1070</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wellbucket</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yarragil 4L</td>
<td>126</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yarraminnup p S</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hansen</td>
<td>80</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>India</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doon Valley</td>
<td>1.45</td>
<td>5.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Oyebande (1988)</td>
</tr>
<tr>
<td>Glenmorga n B</td>
<td>32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sharda et al. (1988); Sharda et al. (1998)</td>
</tr>
</tbody>
</table>

53.5% of catchment cleared between November 1976 and March 1977. 100% cleared in Summer 1976-1977. (first 3 years since reforestation).
<table>
<thead>
<tr>
<th>Treated Catchment</th>
<th>Control Catchment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Catchment</strong></td>
<td><strong>Area (ha)</strong></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Big Bush, New Zealand</strong></td>
<td></td>
</tr>
<tr>
<td>DC1</td>
<td>8.57</td>
</tr>
<tr>
<td><strong>Glenhnu State Forest, New Zealand</strong></td>
<td></td>
</tr>
<tr>
<td>GH2</td>
<td>310</td>
</tr>
<tr>
<td><strong>Maimai, Westland, New Zealand</strong></td>
<td></td>
</tr>
<tr>
<td>M13</td>
<td>4.25</td>
</tr>
<tr>
<td>M14</td>
<td>4.62</td>
</tr>
<tr>
<td>M5</td>
<td>2.31</td>
</tr>
<tr>
<td>M8</td>
<td>3.84</td>
</tr>
<tr>
<td><strong>Uitsoek State Forest, South Africa</strong></td>
<td></td>
</tr>
<tr>
<td>Mokobulaan B 34.6</td>
<td>0.22</td>
</tr>
<tr>
<td><strong>Westfalia, South Africa</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Appendix A**
### Appendix A

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Slope (%)</th>
<th>Mean Elevation (m)</th>
<th>Aspect</th>
<th>Climate</th>
<th>Pre-Treatment Vegetation</th>
<th>Post-Treatment Vegetation</th>
<th>Mean Annual Rainfall (mm)</th>
<th>Mean Annual Streamflow (mm)</th>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Slope (%)</th>
<th>Mean Elevation (m)</th>
<th>Aspect</th>
<th>Climate</th>
<th>Source of info</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Treated Catchment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Westfalia D</td>
<td>39.6</td>
<td>0.33</td>
<td>1050-1320</td>
<td>SE</td>
<td>Sub Tropical with Summer rainfall season</td>
<td>transitional between evergreen high forest and deciduous woodland</td>
<td>Eucalyptus grandis</td>
<td>1253</td>
<td>590</td>
<td>Westfalia B</td>
<td>32.6</td>
<td>0.42</td>
<td>1140-1420</td>
<td>SE</td>
<td>1253</td>
<td>492</td>
</tr>
<tr>
<td>Taiwan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Control Catchment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Riparian zone (10%) of area cut in 1981. 83% afforested with Eucalyptus grandis in 1983</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Beaver Creek, Arizona, USA

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Slope (%)</th>
<th>Mean Elevation (m)</th>
<th>Aspect</th>
<th>Climate</th>
<th>Regrowth</th>
<th>Mean Annual Rainfall (mm)</th>
<th>Mean Annual Streamflow (mm)</th>
<th>Source of info</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS 12</td>
<td>184</td>
<td>2150</td>
<td>SW</td>
<td></td>
<td>Cool and humid with long, cold winters and short, cool summers</td>
<td>Lodgepole pine on all lower and mid-south slopes, and alpine tundra above the timber line</td>
<td>Lexen Creek</td>
<td>124</td>
<td>3002-3536</td>
</tr>
<tr>
<td>WS 14</td>
<td>546</td>
<td>2194</td>
<td>S</td>
<td></td>
<td></td>
<td>Regrowth</td>
<td>Lexen Creek</td>
<td>124</td>
<td>3002-3536</td>
</tr>
<tr>
<td>WS 16</td>
<td>102</td>
<td>2164</td>
<td>SE</td>
<td></td>
<td>Uneven aged stands of ponderosa pine</td>
<td>Regrowth</td>
<td>Lexen Creek</td>
<td>124</td>
<td>3002-3536</td>
</tr>
<tr>
<td>WS 17</td>
<td>121</td>
<td>2115</td>
<td>SW</td>
<td></td>
<td>Watershed 18</td>
<td>66</td>
<td>2054</td>
<td>98</td>
<td>Baker (1986)</td>
</tr>
<tr>
<td>WS 8</td>
<td>730</td>
<td>2225</td>
<td>W</td>
<td></td>
<td>30% harvested in irregular shaped clear-cuts, varying in size from 1 to 6 ha (Summers of 1983-1984)</td>
<td>Regrowth</td>
<td>Lexen Creek</td>
<td>124</td>
<td>3002-3536</td>
</tr>
<tr>
<td>WS 9</td>
<td>454</td>
<td>2194</td>
<td>W</td>
<td></td>
<td>31% strip cut with thinning</td>
<td>Regrowth</td>
<td>Lexen Creek</td>
<td>124</td>
<td>3002-3536</td>
</tr>
</tbody>
</table>

#### Fraser Experimental Forest, USA

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Slope (%)</th>
<th>Mean Elevation (m)</th>
<th>Aspect</th>
<th>Climate</th>
<th>Regrowth</th>
<th>Mean Annual Rainfall (mm)</th>
<th>Mean Annual Streamflow (mm)</th>
<th>Source of info</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deadhorse Creek - North Fork</td>
<td>41</td>
<td></td>
<td></td>
<td></td>
<td>Cool and humid with long, cold winters and short, cool summers</td>
<td>Regrowth</td>
<td>Lexen Creek</td>
<td>124</td>
<td>3002-3536</td>
</tr>
<tr>
<td>Deadhorse Creek Upper Basin</td>
<td>78</td>
<td></td>
<td></td>
<td></td>
<td>Lodgepole pine on all lower and mid-south slopes, and alpine tundra above the timber line</td>
<td>Regrowth</td>
<td>Lexen Creek</td>
<td>124</td>
<td>3002-3536</td>
</tr>
</tbody>
</table>

#### Caspar Creek, California, USA

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (ha)</th>
<th>Slope (%)</th>
<th>Mean Elevation (m)</th>
<th>Source of info</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Fork</td>
<td>424</td>
<td>37-320</td>
<td>Mediterranean, dry summers.</td>
<td>Keppeler and Ziemer (1990); Wright et al. (1990)</td>
</tr>
<tr>
<td>Plynlimon, United Kingdom</td>
<td>1055</td>
<td>37-320</td>
<td>Mediterranean, dry summers.</td>
<td>Keppeler and Ziemer (1990); Wright et al. (1990)</td>
</tr>
<tr>
<td>Severn</td>
<td>540</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kirktown</td>
<td>685</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix B - Results of adjusting flow duration curves for changes in forest cover – All catchments

Pine Creek

Figure B - 1: Pine Creek predicted FDC showing both log and linear views of response.
Red Hill

Figure B - 2: Red Hill predicted FDC showing both log and liner views of response.
Figure B - 3: Don predicted FDC showing both log and liner views of response.
Figure B - 4: Lemon predicted FDC showing both log and liner views of response.
Wight

Figure B - 5: Wight predicted FDC showing both log and linear views of response.
Figure B - 6: Glendhu predicted FDC showing both log and liner views of response.
Figure B - 7: Bosboukloof predicted FDC showing both log and liner views of response.
Appendix B

Biesievlei

Figure B - 8: Biesievlei predicted FDC showing both log and liner views of response.
Cathedral Peak II

Figure B - 9: Cathedral Peak II predicted FDC showing both log and linear views of response.
Figure B - 10: Cathedral Peak III predicted FDC showing both log and linear views of response.
Figure B - 11: Lambrechtsbos A predicted FDC showing both log and linear views of response.
Lambrechtsbos B

Figure B - 12: Lambrechtsbos B predicted FDC showing both log and liner views of response.
Figure B - 13: Tierkloof predicted FDC showing both log and liner views of response.
Figure B - 14: Mokobulaan A predicted FDC showing both log and liner views of response.
Figure B - 15: Mokobulaan B predicted FDC showing both log and liner views of response.
Westfalia

Figure B - 16: Westfalia predicted FDC showing both log and linear views of response.
Figure B - 17: Witklip predicted FDC showing both log and liner views of response.