I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a degree to any other University or Institution.

_______________________________________

Gregory Paul Raper
ACKNOWLEDGEMENTS

Like every PhD candidate, I owe my greatest vote of thanks to my supervisor. George Kuczera was always full of encouragement, even when I perhaps did deserved a hard word or two. George always expressed such a level of faith in me that I felt I would let him down if I didn’t achieve at the highest possible level, and I’m grateful for the motivation that this gave me.

I would like to thank Gary Willgoose for putting up with all my silly questions when he was trying to achieve his own goals, which were high and which also provided me with further inspiration.

I would like to thank John Ruprecht, Greg May and Bob Stokes of the Water Authority of W.A. for providing catchment streamflow and climate data. David Williamson, Jeff Turner and Colin Johnson, of CSIRO Water Resources, also provided catchment data and discussion about catchment processes. I also wish to thank Murugesu Sivapalan and Neil Viney for making the LASCAM model available for this work. The Land and Water Resources Research and Development Corporation funded a portion of this work under project 88/71, for which I am grateful. I would like to thank Marek Mroczkowski for his work on extending the methodology presented here to catchments undergoing landuse change. I acknowledge the great support of my colleagues in Agriculture Western Australia, especially Richard George, who provided me with support and inspired me with their dedication and breadth of knowledge.

Lastly, I thank my wife, Maria, and sons, Kyle and Cameron, for their seemingly endless love and patience.
# Table of Contents

1 Introduction ....................................................................................................................... 1  
1.1 What is a Conceptual Catchment Model? ................................................................... 2  
1.2 Thesis Objective ........................................................................................................ 3  
1.3 Thesis Overview .......................................................................................................... 4  

2 Applications of Lumped Catchment Models ................................................................. 6  
2.1 Evolution of Lumped Catchment Models ................................................................ 6  
2.2 Prediction of Streamflow from Gauged and Ungauged Catchments .................... 7  
2.3 Prediction of Unobserved Catchment Responses ................................................... 7  
2.4 Prediction of Catchment Water Quality .................................................................... 10  
2.5 Summary ................................................................................................................... 12  

3 Problem Definition ......................................................................................................... 13  
3.1 Klemes’ Hierarchical Scheme for Testing of Hydrologic Models ....................... 13  
3.1.1 Stationary Conditions ...................................................................................... 15  
3.1.2 Non-Stationary Conditions ............................................................................. 16  
3.1.3 Some Contemporary Applications of Klemes’ Hierarchical Scheme for Testing of Hydrologic Models ................................................................. 17  
3.2 Difficulties Commonly Encountered in Model Calibration ................................. 18  
3.2.1 The Assumption of Perfect Knowledge ......................................................... 18  
3.2.2 Multiple Optima and Parameter Identifiability .............................................. 19  
3.3 Sources of Error in Catchment Model Predictions ............................................. 22  
3.4 Summary ................................................................................................................... 23  

4 Proposed Methodology ................................................................................................. 24  
4.1 Popper’s Model of The Scientific Method ............................................................. 25  
4.1.1 Degrees of Falsifiability ................................................................................. 27  
4.2 A Model Filter ......................................................................................................... 28  
4.3 The Principle of Parsimony ................................................................................... 30  
4.4 Statistical Techniques for Model Calibration and Hypothesis Testing .............. 31  
4.5 Increasing the Power of Data: Tracers and Other Hydrologic Data ..................... 33  
4.6 Choosing an Approach to Hypothesis Testing .................................................... 35  
4.7 Summary ................................................................................................................... 37  

5 Statistical Framework ................................................................................................... 39  
5.1 Basic Principles ....................................................................................................... 40  
5.2 Error Models .......................................................................................................... 40  
5.2.1 Least Squares Error Model ............................................................................. 40  
5.2.2 Error Model Diagnostics ............................................................................... 41  
5.2.3A More General Error Model ........................................................................... 42
5.3 Parameter Optimisation using Bayesian Inference ......................................................44
  5.3.1 Multiple Response Optimisation ...........................................................................46
  5.3.2 Parameter Transformations .................................................................................47
5.4 Response Surface Plots ..............................................................................................48
5.5 Prediction and Confidence Limits .............................................................................48
5.6 Summary ....................................................................................................................49
6 Case Study: Development of the CATPRO Model ..........................................................51
  6.1 Model Rationale and Philosophy .............................................................................51
  6.2 Catchment Water Balance Model ............................................................................53
    6.2.1 Rainfall Interception .........................................................................................53
    6.2.2 A Store .............................................................................................................54
    6.2.3B Store ..............................................................................................................59
    6.2.4 Groundwater Store .........................................................................................60
  6.3 Catchment Salinity Balance Model ............................................................................62
    6.3.1 Chloride as a Natural Tracer .............................................................................62
    6.3.2 Model Formulation .........................................................................................63
  6.4 Summary ....................................................................................................................66
7 Case Study Catchment ....................................................................................................68
  7.1 Rainfall and Saltfall ..................................................................................................71
  7.2 Streamflow and Chloride Export ............................................................................73
  7.3 Evapotranspiration ..................................................................................................73
  7.4 Groundwater Levels ...............................................................................................75
  7.5 Profile Chloride Storage .........................................................................................77
  7.6 Stable Isotope Observations ...................................................................................78
  7.7 Other Hydrologic Data ...........................................................................................78
  7.8 Summary ...................................................................................................................79
8 Streamflow Calibration ...................................................................................................80
  8.1 Base Case Streamflow Calibration ...........................................................................80
  8.2 Effect of Box-Cox Transformations on Predicted Responses and Parameter Identifiability ..........................................................90
    8.2.1 Box-Cox $\lambda = 0.5$ .......................................................................................90
    8.2.2 Box-Cox $\lambda = 0.25$ ....................................................................................96
  8.3 Split Sample Test .....................................................................................................103
  8.4 Prediction of Unobserved Catchment Responses ....................................................108
    8.4.1 Groundwater Recharge .................................................................................109
    8.4.2 Actual Evapotranspiration .............................................................................110
  8.5 Effect of Relaxing Some Constraints on Model Parameters ....................................111
    8.5.1 Groundwater Leakage Unknown .....................................................................111
    8.5.2 Throughfall Parameters Unknown .................................................................114
LIST OF FIGURES

Figure 6.1: Schematic of CATPRO conceptual catchment water balance model. .................................................................................................................54

Figure 6.2: Conceptualisation of CATPRO A store showing perched water table..............................................................................................55

Figure 7.1: Location map for the Salmon Catchment in the catchment of the Wellington Reservoir which is fed by the Collie River in the south-west of Western Australia, rainfall isohyets are also shown. Other experimental catchments in the Collie River Basin are also marked (after Williamson et al., 1987)......................69

Figure 7.2: Salmon Catchment, showing topographic contours, stream gauging station, pluviographs and piezometer locations (after Stokes, 1985)........................................................................................................................................71

Figure 7.3: Monthly rainfall data for Salmon Catchment, south-west Western Australia, derived by Thiessen-weighting of daily rainfalls observed at three pluviometers. (Source: Water Authority of W.A.).........................................................................................................................72

Figure 7.4: Time series of monthly Class A pan evaporation and Morton’s wet environment evapotranspiration for Salmon Catchment, April 1974 to March 1983. ........................................................................75

Figure 7.5: Time series of piezometric heads for four representative piezometers at Salmon Catchment between April 1974 and March 1983, inclusive (data courtesy of CSIRO Division of Water Resources). ........................................................................................................76

Figure 7.6: Time series of catchment average piezometric head for Salmon Catchment. ..........................................................................................77

Figure 8.1: Monthly streamflow for Salmon Catchment predicted by CATPRO calibrated to streamflow data alone, Box-Cox $\lambda = 1.0$. ....................................................................................................................82

Figure 8.2: Time series of predicted contributions to streamflow for CATPRO calibrated to Salmon streamflow data using Box-Cox $\lambda = 1.0$. ..........................................................................................................................82

Figure 8.3: Time series of CATPRO conceptual stores predicted for Salmon Catchment following calibration to streamflow data using Box-Cox $\lambda = 1.0$. .................................................................................................................84

Figure 8.4: Scatter plot of residuals against predicted streamflow for CATPRO calibrated to Salmon streamflow data using Box-Cox $\lambda = 1.0$. ..............................................................................................................85
Figure 8.5: Residual time series plot for streamflow predicted by CATPRO calibrated to Salmon streamflow data using Box-Cox $\lambda = 1.0$. .................................................................86

Figure 8.6: Residual autocorrelation plot for streamflow predicted by CATPRO calibrated to Salmon streamflow data using Box-Cox $\lambda = 1.0$. .................................................................86

Figure 8.7: Residual normal probability plot for CATPRO calibrated to Salmon streamflow data using Box-Cox $\lambda = 1.0$. .................................................................87

Figure 8.8: Residual cumulative periodogram plot for CATPRO calibrated to Salmon streamflow data using Box-Cox $\lambda = 1.0$. .................................................................87

Figure 8.9: CATPRO response surface plot, rank 1 and rank 2 principal components for calibration to Salmon streamflow data using Box-Cox $\lambda = 1.0$. .................................................................88

Figure 8.10: CATPRO response surface plot, rank 2 and rank 3 principal components for calibration to Salmon streamflow data using Box-Cox $\lambda = 1.0$. .................................................................89

Figure 8.11: CATPRO response surface plot, rank 6 and rank 7 principal components for calibration to Salmon streamflow data using Box-Cox $\lambda = 1.0$. .................................................................89

Figure 8.12: Monthly streamflow for Salmon Catchment predicted by CATPRO calibrated to streamflow data alone, Box-Cox $\lambda = 0.5$. .................................................................91

Figure 8.13: Scatter plot of residuals against predicted streamflow for CATPRO calibrated to Salmon streamflow data using Box-Cox $\lambda = 0.5$. .................................................................91

Figure 8.14: Residual normal probability plot for CATPRO calibrated to Salmon streamflow data using Box-Cox $\lambda = 0.5$. .................................................................92

Figure 8.15: Residual cumulative periodogram plot for CATPRO calibrated to Salmon streamflow data using Box-Cox $\lambda = 0.5$. .................................................................93

Figure 8.16: Time series of predicted contributions to streamflow for CATPRO calibrated to Salmon streamflow data using Box-Cox $\lambda = 0.5$. .................................................................94

Figure 8.17: Time series of CATPRO conceptual stores predicted for Salmon Catchment following calibration to streamflow data using Box-Cox $\lambda = 0.5$. .................................................................94

Figure 8.18: CATPRO response surface plot, rank 4 and rank 5 principal components for calibration to Salmon streamflow data using Box-Cox $\lambda = 0.5$. .................................................................96
Figure 8.19: CATPRO response surface plot, rank 1 and rank 2 principal components for calibration to Salmon streamflow data using Box-Cox $\lambda = 0.5$, with parameters $bf$, $bf_{crit}$ and $gws0$ fixed. .................................................................97

Figure 8.20: Monthly streamflow for Salmon Catchment predicted by CATPRO calibrated to streamflow data alone, Box-Cox $\lambda = 0.25$ .................................................................97

Figure 8.21: Scatter plot of residuals against predicted streamflow for CATPRO calibrated to Salmon streamflow data using Box-Cox $\lambda = 0.25$. .................................................................98

Figure 8.22: Residual normal probability plot for CATPRO calibrated to Salmon streamflow data using Box-Cox $\lambda = 0.25$ .................................................................99

Figure 8.23: Residual cumulative periodogram plot for CATPRO calibrated to Salmon streamflow data using Box-Cox $\lambda = 0.25$. .................................................................99

Figure 8.24: Time series of predicted contributions to streamflow for CATPRO calibrated to Salmon streamflow data using Box-Cox $\lambda = 0.25$. .................................................................101

Figure 8.25: Time series of CATPRO conceptual stores predicted for Salmon Catchment following calibration to streamflow data using Box-Cox $\lambda = 0.25$. .................................................................101

Figure 8.26: CATPRO response surface plot, rank 2 and rank 3 principal components for calibration to Salmon streamflow data using Box-Cox $\lambda = 0.25$. .................................................................103

Figure 8.27: CATPRO response surface plot, rank 1 and rank 2 principal components for calibration to Salmon streamflow data using Box-Cox $\lambda = 0.25$, with parameter $bf_{crit}$ fixed. .................................................................104

Figure 8.28: Monthly streamflow for Salmon Catchment predicted by CATPRO calibrated to the first 5 years of streamflow data as a split sample test, Box-Cox $\lambda = 0.5$. .................................................................105

Figure 8.29: Time series of predicted contributions to streamflow for Salmon Catchment following calibration of CATPRO to the first 5 years of streamflow data as a split sample test, Box-Cox $\lambda = 0.5$. .................................................................106

Figure 8.30: Time series of CATPRO conceptual stores predicted for Salmon Catchment following calibrated to the first 5 years of streamflow data as a split sample test, Box-Cox $\lambda = 0.5$. .................................................................106

Figure 8.31: Monthly streamflow for Salmon Catchment predicted by CATPRO calibrated to the first 5 years of streamflow data as a split sample test, Box-Cox $\lambda = 0.5$ and groundwater store inactive. .................................................................108
Figure 8.32: Time series of predicted contributions to streamflow for Salmon Catchment following calibration of CATPRO to the first 5 years of streamflow data as a split sample test, Box-Cox $\lambda = 0.5$ and groundwater store inactive. ...........................................108

Figure 8.33: Time series of unobserved groundwater recharge and 90% confidence limits predicted for Salmon Catchment by CATPRO calibrated to streamflow data, Box-Cox $\lambda = 0.5$ ...............110

Figure 8.34: Time series of unobserved catchment averaged evapotranspiration and 90% confidence limits predicted for Salmon Catchment by CATPRO calibrated to streamflow data, Box-Cox $\lambda = 0.5$ ..........................................................................111

Figure 8.35: Time series of predicted streamflow and 90% prediction limits produced for Salmon Catchment by CATPRO calibrated to streamflow data without prior knowledge of groundwater leakage, Box-Cox $\lambda = 0.5$ .........................................................................................113

Figure 8.36: Time series of unobserved catchment averaged recharge and 90% confidence limits predicted for Salmon Catchment by CATPRO calibrated to streamflow data without prior knowledge of groundwater leakage, Box-Cox $\lambda = 0.5$ .................113

Figure 8.37: Time series of unobserved catchment averaged evapotranspiration and 90% confidence limits predicted for Salmon Catchment by CATPRO calibrated to streamflow data without prior knowledge of groundwater leakage, Box-Cox $\lambda = 0.5$ .........................................................................................114

Figure 8.38: Time series of predicted streamflow and 90% prediction limits produced for Salmon Catchment by CATPRO calibrated to streamflow data without prior knowledge of throughfall, Box-Cox $\lambda = 0.5$ .........................................................................................115

Figure 8.39: Time series of unobserved catchment averaged recharge and 90% confidence limits predicted for Salmon Catchment by CATPRO calibrated to streamflow data without prior knowledge of throughfall, Box-Cox $\lambda = 0.5$ .........................................................................................116

Figure 8.40: Time series of unobserved catchment averaged evapotranspiration and 90% confidence limits predicted for Salmon Catchment by CATPRO calibrated to streamflow data without prior knowledge of throughfall, Box-Cox $\lambda = 0.5$ .........................................................................................116

Figure 9.1: Groundwater storage - discharge relationship showing the effects of model parameters $bf_{max}$ and $bf_{crit}$ ........................................121

Figure 9.2: Monthly streamflow for Salmon Catchment predicted by CATPRO calibrated to streamflow, stream chloride export and changes in piezometric head, Box-Cox $\lambda = 0.5$, 0.5, and 1.0 respectively. ..................................................123
Figure 9.3: Monthly chloride exported in streamflow for Salmon Catchment predicted by CATPRO calibrated to streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5, \text{ and } 1.0$ respectively. ................................................123

Figure 9.4: Calculated catchment averaged piezometric heads for the deep aquifer at Salmon Catchment and groundwater storage predicted by CATPRO calibrated to streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5, \text{ and } 1.0$ respectively. ...........................................................124

Figure 9.5: Time series of predicted contributions to streamflow for Salmon Catchment made by CATPRO calibrated to streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5, \text{ and } 1.0$ respectively. .........................................................................................126

Figure 9.6: Time series of predicted contributions to stream chloride export for Salmon Catchment made by CATPRO calibrated to streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5, \text{ and } 1.0$ respectively. .........................................................................................126

Figure 9.7: Time series of predicted chloride concentrations of contributions to streamflow for Salmon Catchment made by CATPRO calibrated to streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5, \text{ and } 1.0$ respectively. ........................................................................................................127

Figure 9.8: Time series of predicted mass of chloride in model stores for Salmon Catchment made by CATPRO calibrated to streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5, \text{ and } 1.0$ respectively. ........................................................................................................127

Figure 9.9: Scatter plot of residuals against predicted streamflow for CATPRO calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5, \text{ and } 1.0$ respectively. ................................................132

Figure 9.10: Normal probability plot of streamflow residuals for CATPRO calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5, \text{ and } 1.0$ respectively. ................................................132

Figure 9.11: Cumulative periodogram of streamflow residuals for CATPRO calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5, \text{ and } 1.0$ respectively. ................................................133
Figure 9.12: Autocorrelation plot for streamflow residuals for CATPRO calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5,$ and $1.0$ respectively.................................................................133

Figure 9.13: Scatter plot of residuals against predicted streamflow chloride export for CATPRO calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5,$ and $1.0$ respectively.................................................................134

Figure 9.14: Normal probability plot of streamflow chloride export residuals for CATPRO calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5,$ and $1.0$ respectively.................................................................135

Figure 9.15: Cumulative periodogram of streamflow chloride export residuals for CATPRO calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5,$ and $1.0$ respectively.................................................................135

Figure 9.16: Autocorrelation plot for streamflow chloride export residuals for CATPRO calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5,$ and $1.0$ respectively.................................................................136

Figure 9.17: Scatter plot of residuals against predicted changes in groundwater storage for CATPRO calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5,$ and $1.0$ respectively.................................................................137

Figure 9.18: Normal probability plot of change in groundwater storage residuals for CATPRO calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5,$ and $1.0$ respectively.................................................................137

Figure 9.19: Cumulative periodogram of change in groundwater storage residuals for CATPRO calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5,$ and $1.0$ respectively.................................................................138

Figure 9.20: Autocorrelation plot for change in groundwater storage residuals for CATPRO calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5,$ and $1.0$ respectively.................................................................138
Figure 9.21: CATPRO response surface plot, rank 1 and rank 2 principal components for calibration to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5, \text{ and } 1.0$ respectively. ..........................................................139

Figure 9.22: CATPRO response surface plot, rank 2 and rank 3 principal components for calibration to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5, \text{ and } 1.0$ respectively. ..........................................................140

Figure 9.23: CATPRO response surface plot, rank 12 and rank 13 principal components for calibration to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5, \text{ and } 1.0$ respectively. ..........................................................141

Figure 9.24: Time series of unobserved groundwater recharge and 90% confidence limits predicted for Salmon Catchment following calibration to streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5, \text{ and } 1.0$ respectively. ..........................................................142

Figure 9.25: Time series of unobserved catchment averaged evapotranspiration and 90% confidence limits predicted for Salmon Catchment following calibration to streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5, \text{ and } 1.0$ respectively. ..........................................................143

Figure 10.1: Schematic of LASCAM water balance model showing conceptual stores and fluxes (after Viney and Sivapalan, 1995). See the text for explanations of the model fluxes.................150

Figure 10.2: Monthly streamflow for Salmon Catchment predicted by LASCAM calibrated to streamflow, stream chloride export and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25, \text{ and } 1.0$ respectively..........................................................165

Figure 10.3: Monthly stream chloride export for Salmon Catchment predicted by LASCAM calibrated to streamflow, stream chloride export and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25, \text{ and } 1.0$ respectively..........................................................166

Figure 10.4: Calculated catchment averaged piezometric heads for the deep aquifer at Salmon Catchment and groundwater storage predicted by LASCAM calibrated to streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25, \text{ and } 1.0$ respectively. ..........................................................166
Figure 10.5: Time series of predicted contributions to streamflow for Salmon Catchment made by LASCAM calibrated to streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25, \text{ and } 1.0$ respectively. ................................................................. 167

Figure 10.6: Time series of predicted model storages for Salmon Catchment made by LASCAM calibrated to streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25, \text{ and } 1.0$ respectively. ............................................ 167

Figure 10.7: Time series of predicted contributions to stream chloride export for Salmon Catchment made by LASCAM calibrated to streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25, \text{ and } 1.0$ respectively. ................................................................. 168

Figure 10.8: Time series of predicted chloride concentrations of contributions to streamflow for Salmon Catchment made by LASCAM calibrated to streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25, \text{ and } 1.0$ respectively. ................................................................. 168

Figure 10.9: Time series of predicted mass of chloride in model stores for Salmon Catchment made by LASCAM calibrated to streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5, 0.5, \text{ and } 1.0$ respectively. ................................................................. 169

Figure 10.10: Scatter plot of residuals against predicted streamflow for LASCAM calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25, \text{ and } 1.0$ respectively. ......................................................... 170

Figure 10.11: Normal probability plot of streamflow residuals for LASCAM calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25, \text{ and } 1.0$ respectively. ......................................................... 171

Figure 10.12: Cumulative periodogram of streamflow residuals for LASCAM calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25, \text{ and } 1.0$ respectively. ......................................................... 171

Figure 10.13: Autocorrelation plot for streamflow residuals for LASCAM calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25, \text{ and } 1.0$ respectively. ......................................................... 172
Figure 10.14: Scatter plot of residuals against predicted chloride export for LASCAM calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25,$ and $1.0$ respectively. ............................................173

Figure 10.15: Normal probability plot of chloride export residuals for LASCAM calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25,$ and $1.0$ respectively. ............................................173

Figure 10.16: Cumulative periodogram of chloride export residuals for LASCAM calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25,$ and $1.0$ respectively. ............................................174

Figure 10.17: Autocorrelation plot for chloride export residuals for LASCAM calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25,$ and $1.0$ respectively. ............................................174

Figure 10.18: Scatter plot of residuals against predicted changes in groundwater storage for LASCAM calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25,$ and $1.0$ respectively. ............................................175

Figure 10.19: Normal probability plot of changes in groundwater storage residuals for LASCAM calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25,$ and $1.0$ respectively. ............................................176

Figure 10.20: Cumulative periodogram of changes in groundwater storage residuals for LASCAM calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25,$ and $1.0$ respectively. ............................................176

Figure 10.21: Autocorrelation plot for changes in groundwater storage residuals for LASCAM calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25,$ and $1.0$ respectively. ............................................177

Figure 10.22: LASCAM response surface plot, rank 3 and rank 4 principal components for calibration to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25,$ and $1.0$ respectively. ............................................178
Figure 10.23: LASCAM response surface plot, rank 4 and rank 5 components for calibration to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25, \text{ and } 1.0$ respectively. .................................................................179

Figure 10.24: LASCAM response surface plot, rank 7 and rank 8 principal components for calibration to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25, \text{ and } 1.0$ respectively. .................................................................180

Figure 10.25: Time series of unobserved groundwater recharge and 90% confidence limits predicted for Salmon Catchment following calibration of LASCAM to streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25, \text{ and } 1.0$ respectively.................................................................182

Figure 10.26: Time series of unobserved catchment averaged evapotranspiration and 90% confidence limits predicted for Salmon Catchment following calibration of LASCAM to streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25, 0.25, \text{ and } 1.0$ respectively.................................................................182

Figure 10.27: Time series of unobserved catchment averaged evapotranspiration predicted by CATPRO and by LASCAM for Salmon Catchment following calibration to streamflow, stream water salinity and changes in piezometric head. ..................183
LIST OF TABLES

Table 5.1: Parameter transformations available in NLFIT Bayesian nonlinear regression suite and their effects, where $\beta$ and $\beta_T$ are the parameter and its transformed value respectively. .......................47

Table 6.1: CATPRO model parameter definitions and units........................................67

Table 8.1: Posterior parameter distribution for calibration of the CATPRO model to Salmon streamflow data for a 10 year record using Box-Cox $\lambda = 1.0$. ................................................................................83

Table 8.2: Posterior correlation matrix of parameters for CATPRO calibrated to Salmon streamflow data using Box-Cox $\lambda = 1.0$. ........................................................................................................84

Table 8.3: Posterior parameter distribution for calibration of the CATPRO model to Salmon streamflow data for a 10 year record using Box-Cox $\lambda = 0.5$. .................................................................95

Table 8.4: Posterior parameter distribution for calibration of the CATPRO model to Salmon streamflow data for a 10 year record using Box-Cox $\lambda = 0.25$. .................................................................102

Table 8.5: Posterior parameter distribution for calibration of the CATPRO model to Salmon streamflow data for the first 5 years of record as a split sample test, Box-Cox $\lambda = 0.5$..........................107

Table 9.1: Calibration statistics for CATPRO calibrated to streamflow, stream water salinity and changes in piezometric head at Salmon Catchment, Box-Cox $\lambda = 0.5$, 0.5, and 1.0 respectively. .................................................................124

Table 9.2: Posterior parameter distribution for CATPRO hydrosalinity model calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5$, 0.5, and 1.0 respectively. .................................................................129

Table 9.3: Posterior correlation matrix of parameters for CATPRO calibrated to streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.5$, 0.5, and 1.0 respectively. .................................................................130

Table 10.1: LASCAM model parameters and definitions (after Sivapalan et al., 1996a, 1996b and Viney and Sivapalan, 1995). ........................................................................................................151
Table 10.2: Posterior parameter distribution for LASCAM hydrosalinity model calibrated to Salmon Catchment streamflow, stream water salinity and changes in piezometric head, Box-Cox $\lambda = 0.25$, $0.25$, and $1.0$ respectively. Five parameters not subject to calibration due to large standard deviations relative to expected values are shown as fixed. ...................................162

Table 10.3: LASCAM parameters fixed due to large standard deviations relative to expected values. See text for explanation.........................163

Table 10.4: Calibration statistics for LASCAM calibrated to streamflow, stream water salinity and changes in piezometric head at Salmon Catchment, Box-Cox $\lambda = 0.25$, $0.25$, and $1.0$ respectively. .........................................................................................163

Table 10.5: Posterior correlation matrix of parameters for LASCAM model calibrated to streamflow, stream water salinity and changes in piezometric head at Salmon Catchment, Box-Cox $\lambda = 0.25$, $0.25$, and $1.0$ respectively. Correlation coefficients $> 0.9$ are highlighted.................................................................164
ABSTRACT

During the latter part of the 1980s there was some debate in the literature that hydrology was not practised as a science but as an engineering technology. Hydrologic modelling was seen as devoid of a scientific basis, conceptual catchment modelling in particular, because the practice of calibrating a model to the response that was the subject of investigation was seen as “fudging” a catchment water balance. Presented here is a methodology, based on Popper’s (1959) theory of the nature of the scientific method, to more rigorously test the hypotheses about the catchment water balance that constitute a conceptual catchment model. The methodology has three main elements. Firstly, the calibration of a conceptual catchment model to multiple catchment responses to constrain the model behaviour. Secondly, the application of established statistical techniques to critically assess model predictions and errors; and, thirdly the principle of parsimony, the search for the simplest model that fully explains the data. The methodology is demonstrated by way of a case study in which a conceptual catchment model is proposed and rigorously tested. This is followed by a comparison with another model developed from the same conceptual base, but without reference to the proposed methodology.


**Preface**

The bulk of the research reported in this thesis was carried out between March 1990 and July 1992. The application of the statistical techniques described in Chapter 5 and the prediction of unobserved catchment responses, such as catchment averaged groundwater recharge, are described in Raper and Kuczera (1991). The use of multi-response time series data to provide greater power to falsify model hypotheses is reported in Raper and Kuczera (1993a, 1993b).

The methodology laid down in this thesis has been further strengthened by introducing the more demanding tests of model hypotheses that can be exerted by calibration to multi-response time series data that cover a period of catchment response to changes in landuse. Examples of the power of multi-response data and non-stationary hydrologic regime are given in the subsequent work of Kuczera *et al.* (1993) and more recently by Mroczkowski *et al.* (1997).