Determining Trade-off between Sustainable Yield and Baseflow in the Kulnura – Mangrove Mountain Aquifer System using Simulation – Optimisation Modelling

by

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CERTIFICATE OF AUTHORSHIP / ORGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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TABLE OF CONTENTS

CERTIFICATE OF AUTHORSHIP / ORGINALITY .... **I**

ACKNOWLEDGMENTS .... **II**

TABLE OF CONTENTS .... **IV**

LIST OF ILLUSTRATIONS .... **IX**

LIST OF TABLES .... **XIX**

LIST OF SYMBOLS .... **XXIV**

ABSTRACT .... **XXIX**

CHAPTER ONE **1**

1.0 INTRODUCTION **1**

- 1.1 BACKGROUND 1
- 1.2 RESEARCH OBJECTIVES 1
- 1.3 THESIS STRUCTURE 2

CHAPTER TWO **4**

2.0 LITERATURE REVIEW AND METHODOLOGY **4**

- 2.1 INTRODUCTION 4
- 2.2 WATER SHARING PLAN 4
  - *2.2.1 Water Sharing Plan for Kulnura Mangrove Mountain Groundwater Sources* *5*
    - 2.2.1.1 Area of the Plan 6
  - *2.2.2 Water Sharing Plan for Ourimbah Creek Water Source* *10*
  - *2.2.3 Water Sharing Plan for Jilliby Jilliby Creek Water Source* *14*
- 2.3 BASEFLOW 18
  - *2.3.1 Baseflow and Importance* *18*
  - *2.3.2 Baseflow Computation* *20*
    - 2.3.2.1 Baseflow Separation 20
      - 2.3.2.1.1 Graphical Separation Method 20
      - 2.3.2.1.2 Automated Baseflow Separation Techniques 21
        - 2.3.2.1.2.1 Recursive Digital Filter 21
        - 2.3.2.1.2.2 Smoothed Minima Technique 23
        - 2.3.2.1.2.3 Chapman Algorithm 23
        - 2.3.2.1.2.4 PART Model 24
        - 2.3.2.1.2.5 Comparison between Smoothed Minima Technique and Recursive Digital Filter 24
        - 2.3.2.1.2.6 Comparison between PART Model and Recursive Digital Filter 27
        - 2.3.2.1.2.7 Comparison between Chapman Algorithm and Recursive Digital Filter 27
        - 2.3.2.1.2.8 Investigating Filter Parameter and Number of Passes 28
        - 2.3.2.1.2.9 Summary of Automated Baseflow Separation Techniques 29

2.3.2.2 Frequency Analysis Method 30
2.3.2.3 Recession Analysis Method 31
2.4 STREAM-AQUIFER INTERACTION 32
2.4.1 Introduction 32
2.4.2 Analytical Solution of Stream Depletion 32
2.4.3 Groundwater and Surface Water Software 36
2.4.3.1 Groundwater Software 36
2.4.3.1.1 MODFLOW 36
2.4.3.1.2 MODFLOW-SURFACT 37
2.4.3.1.3 MODHMS 38
2.4.3.1.4 GSFLOW 38
2.4.3.2 Surface Water Software 39
2.4.3.2.1 SWAT 39
2.4.3.2.2 POTYLDR 39
2.4.3.2.3 HSPF 40
2.4.3.2.4 PRMS 40
2.4.4 Management Applications of Coupling Surface and Groundwater 40
2.4.5 Impact of Aquifer Heterogeneity on River Seepage 44
2.4.6 Streamflow versus Groundwater Pumping 44
2.5 GROUNDWATER MANAGEMENT MODELS OF A STREAM-AQUIFER SYSTEM ...45
2.5.1 Introduction 45
2.5.2 Groundwater Management Models 47
2.5.2.1 Response Matrix Approach 48
2.5.2.2 Embedding Approach 48
2.5.2.2.1 Comparison between Response Matrix Approach and Embedding Approach 49
2.5.2.3 Linked Simulation-Optimisation Approach 51
2.5.3 Comparison between the Results of Simulation Model and Simulation-Optimisation Management Model 51
2.5.4 Stream-Aquifer Management Model and Conjunctive Use Management Model 52
2.5.4.1.1 Objective Functions 52
2.5.4.1.2 Constraints 54
2.5.4.1.3 Groundwater Management Applications on Stream-Aquifer Interactions using Response Matrix Approach 57
2.5.4.1.4 Groundwater Management Application on Stream-Aquifer Interactions using Embedding Approach 66
2.5.4.1.5 Groundwater Management Applications on Stream-Aquifer Interactions using Linked Simulation-Optimisation Approach67
2.6 SIMULATION-OPTIMISATION MODEL APPLICATIONS IN AUSTRALIA 69
2.7 COMPARISON WITH THE PREVIOUS STUDIES AND RESEARCH ORIGINALITY ...70
2.8 RESEARCH METHODOLOGY 73
CHAPTER THREE 76
3.0 STUDY AREA 76
3.1 LOCATION 76
3.2 TOPOGRAPHY 77
3.3 RAINFALL 77

3.4 SURFACE DRAINAGE 77
CHAPTER FOUR 81
4.0 DATA ANALYSIS 81
4.1 RAINFALL DATA 81
4.1.1 Gosford Rainfall Station *81*
4.1.2 Peats Ridge Rainfall Station *85*
4.1.3 Kulnura North Rainfall Station *87*
4.1.4 Laguna Rainfall Station *89*
4.1.5 Residual Rainfall Mass Curve *91*
4.2 TEMPERATURE 94
4.3 EVAPORATION 95
4.4 RELATIVE HUMIDITY 95
4.5 WIND SPEED 97
4.6 STREAM FLOW DATA 97
4.7 MONITORING BORES NETWORK 102
CHAPTER FIVE 113
5.0 GEOLOGY AND HYDROGEOLOGY 113
5.1 GEOLOGY 113
5.1.1 Quaternary Alluvium *114*
5.1.2 Volcanics *114*
5.1.3 Hawkesbury Sandstone *114*
5.1.3.1 Sheet Facies Sandstone 115
5.1.3.2 Massive Facies Sandstone 115
5.1.3.3 Mudstone Facies 115
5.1.3.4 Relationship of the Units 115
5.1.4 Narrabeen Group *116*
5.1.4.1 Gosford Formation 116
5.1.4.1.1 Wyong Sandstone Member 116
5.1.4.1.2 Ourimbah Sandstone Member 116
5.1.4.1.3 Mangrove Sandstone Member 116
5.1.4.2 Clifton Sub-group 117
5.1.5 Structure *117*
5.2 HYDROGEOLOGY 118
5.2.1 Aquifer Systems *118*
5.2.2 Groundwater Movement *119*
5.3 CONCEPTUALIZATION 119
CHAPTER SIX 123
6.0 GROUNDWATER FLOW MODELLING 123
6.1 GENERAL 123
6.2 SELECTION OF A MODEL CODE 123
6.3 GOVERNING EQUATIONS 125
6.4 MODEL DESIGN 126
6.4.1 Model Domain and Grid Size *126*
6.4.2 Input Parameters *126*

6.4.2.1 Topography 126
6.4.2.2 Model Layers 126
6.4.2.3 Hydraulic Conductivity 130
6.4.2.4 Recharge Estimation 132
6.4.2.5 Baseflow Estimation 135
6.4.3 Boundary Conditions 140
6.4.4 Initial Conditions 143
6.4.5 Drainage Network 143
6.5 STEADY-STATE CALIBRATION 146
6.6 TRANSIENT SIMULATION 150
6.6.1 Time Scale Selection 150
6.6.2 Groundwater Usage 151
6.6.3 Transient Model Calibration 153
6.6.4 Transient Model Verification 155
6.6.5 Model Calibration Performance Measures 166
6.6.6 Transient Water Budget 171
6.6.7 Baseflow Simulation 171
6.7 SENSITIVITY ANALYSIS 175
6.8 TRANSIENT MODEL SIMULATION 185

CHAPTER SEVEN 189

7.0 PARTICLE TRACKING 189

7.1 INTRODUCTION 189
7.2 SIMULATION SCENARIOS 189
7.2.1 Scenario 1: Forward Tracking 189
7.2.2 Scenario 2: Backward Tracking 191

CHAPTER EIGHT 194

8.0 OPTIMISATION MODEL 194

8.1 INTRODUCTION 194
8.2 OPTIMISATION MODEL FORMULATION, OBJECTIVE FUNCTION AND CONSTRAINTS 194
8.3 OPTIMAQ SOFTWARE 196
8.4 GAMS CODE 198
8.5 STEADY STATE OPTIMISATION 199
8.5.1 Response Matrix 201
8.5.2 Steady State Optimisation Scenarios 203
8.5.2.1 Scenario 1: Water Sharing Plan Area 204
8.5.2.1.1 Verification and Trade-Off Curve 208
8.5.2.2 Scenario 2: Brisbane-Water Catchment 210
8.5.2.2.1 Verification and Trade-Off Curve 214
8.5.2.3 Scenario 3: Ourimbah Catchment 216
8.5.2.3.1 Verification and Trade-Off Curve 220
8.5.2.4 Scenario 4: Wyong Catchment 223
8.5.2.4.1 Verification and Trade-Off Curve 226
8.5.2.5 Scenario 5: All Catchments 229
8.5.2.5.1 Verification and Trade-Off Curve 235

8.5.2.6 Scenario 6: Hypothetical Bores Network in Water Sharing Plan Area 241
    8.5.2.6.1 Hypothetical Bores Optimisation 244
    8.5.2.6.2 Trade-Off Curve 247
8.5.3 Transient Optimisation Scenarios 251
8.5.3.1 Rainfall-Recharge Analysis 252
8.5.3.2 Optimisation Models 254
    8.5.3.2.1 Trade-Off Curves 272

CHAPTER NINE 283

9.0 SUMMARY AND CONCLUSION 283

9.1 INTRODUCTION 283
9.2 STUDY AREA 284
9.3 METHODOLOGY 284
9.4 DATA ANALYSIS 284
9.5 GEOLOGY 285
9.6 HYDROGEOLOGY AND GROUNDWATER MOVEMENT 286
9.7 CONCEPTUAL MODEL 286
9.8 GROUNDWATER FLOW MODEL 287
9.9 PARTICLE TRACKING 290
9.10 OPTIMISATION MODEL 291
9.11 CONCLUSION 294
9.12 FUTURE WORK 297

REFERENCES 299

APPENDICES 308

APPENDIX A 309

DERIVATION OF THE HYDRAULIC GRADIENT CONSTRAINT 309

APPENDIX B 312

GAMS CODE 312

LIST OF ILLUSTRATIONS

Figure	Title	Page
2.1	Location map of Kulnura Mangrove Mountain Groundwater Sources (shaded area) within the Central Coast Water Management Area	7
2.2	Kulnura Mangrove Mountain Groundwater Sources (8 zones)	9
2.3	Location map of Ourimbah Creek Water Source (shaded area) within the Cental Coast Water Management Area	11
2.4	Ourimbah Creek Water Source	13
2.5	Location map of Jilliby Jilliby Creek Water Source (shaded area) within the Cental Coast Water Management Area	15
2.6	Jilliby Jilliby Creek Water Source	17
2.7	Components of a typical stream hydrograph	19
2.8	Baseflow separation techniques: straight line method (line AB), fixed base method (line ACD) and variable slope method (line ACEB)	21
2.9	Illustration of the slow flow separation filter performance. Two stage filter with $\alpha = 0.8$	23
2.10	Examples of continuous baseflow separation using the smoothed minima technique	25
2.11	Examples of continuous baseflow separation using recursive digital filter	25
2.12	Correlation between BFI indices derived using digital filter and smoothed minima techniques	26
2.13	Baseflow by PART model vs graphical approach	27
2.14	Baseflow by Recursive Digital Filter vs graphical approach	27
2.15	Outline of the problem considered	35
2.16	A comparison between predictions of stream depletion caused by groundwater pumping at 250 m and 1000 m using two different methods: the MODHMS model and the Hunt (1999) solution to a simplified system	43

2.17 General Process of an Optimisation Model 46

2.18 Classification of groundwater management models 50

2.19 Tradeoffs between groundwater withdrawals and minimum streamflow criteria 66

3.1 Location map of the study area 76

3.2 Topographical map of the study area 78

3.3 Rainfall Distribution over the Study Area 79

3.4 Drainage Map of the Study Area 80

4.1 Rainfall Stations, Flow Gauges and Monitoring Bore Location Map 82

4.2 Total annual rainfall variation at Gosford rainfall station during the period 1917 - 2002 84

4.3 Minimum, average and maximum monthly rainfall recorded at Gosford rainfall station for the period July 1916 – May 2003 85

4.4 Total annual rainfall variation at Peats Ridge rainfall station during the period 1982 - 2004 86

4.5 Minimum, average and maximum monthly rainfall recorded at Peats Ridge rainfall station for the period October 1981 – August 2005 87

4.6 Total annual rainfall variation at Kulnura North rainfall station during the period 1960 - 2000 88

4.7 Minimum, average and maximum monthly rainfall recorded at Kulnura North rainfall station for the period October 1959 – November 2001 89

4.8 Total annual rainfall variation at Laguna rainfall station during the period 1960 - 2002 90

4.9 Minimum, average and maximum monthly rainfall recorded at Laguna rainfall station for the period April 1959 – April 2003 91

4.10 Residual Rainfall Mass Curve for Gosford rainfall station 92

4.11 Residual Rainfall Mass Curve for Peats Ridge rainfall station 92

4.12 Residual Rainfall Mass Curve for Kulnura North rainfall station 93

4.13 Residual Rainfall Mass Curve for Laguna rainfall station 93

4.14 Residual Rainfall Mass Curves for all rainfall stations 94

4.15 Monthly averages of the mean, maximum and minimum temperatures at Peats Ridge meteorological station (October1981-May 2003) 95

4.16 Minimum, maximum and averages monthly evaporation rate at Peats Ridge meteorological station (October1981- May 2003) 96

4.17 Average mean monthly relative humidity with minimum and maximum at 9:00 am and 3:00 pm at Peats Ridge meteorological station (October1981- May 2003) 96

4.18 Average mean monthly wind speed with minimum and maximum at 9:00 am and 3:00 pm at Peats Ridge meteorological station (October1981- May 2003) 97

4.19 Residual Mass Curves (Ourimbah CK Flow Gauge # 211013 & Kulnura North Rainfall Station) 98

4.20 Residual Mass Curves (Ourimbah CK Flow Gauge # 211005 & Kulnura North Rainfall Station) 99

4.21 Residual Mass Curves (Jilliby CK Flow Gauge # 211010 & Gosford Rainfall Station) 99

4.22 Residual Mass Curves (Wyong River Flow Gauge # 211014 & Laguna Rainfall Station) 100

4.23 Residual Mass Curves (Wyong River Flow Gauge # 211009 & Laguna Rainfall Station) 100

4.24 Residual Mass Curves (Wyong River Flow Gauge # 211007 & Laguna Rainfall Station) 101

4.25 Residual Mass Curves (Mangrove CK Flow Gauge # 212039 & Gosford Rainfall Station) 101

4.26 Residual Mass Curves (Mangrove CK Flow Gauge # 212019 & Gosford Rainfall Station) 102

4.27 Monitoring Bores Location Map 104

4.28 Groundwater Hydrograph for Bore 64051 and Residual Rainfall Mass Curve for Peats Ridge Rainfall Station 106

4.29 Groundwater Hydrograph for Bore 75009 and Residual Rainfall Mass Curve for Peats Ridge Rainfall Station 106

4.30 Groundwater Hydrograph for Bore 75010 and Residual Rainfall Mass Curve for Peats Ridge Rainfall Station 107

4.31 Groundwater Hydrograph for Bore 75013~1 and Residual Rainfall Mass Curve for Peats Ridge Rainfall Station 107

4.32 Groundwater Hydrograph for Bore 75013~2 and Residual Rainfall Mass Curve for Peats Ridge Rainfall Station 108

4.33 Groundwater Hydrograph for Bore 75013~3 and Residual Rainfall Mass Curve for Peats Ridge Rainfall Station 108

4.34 Groundwater Hydrograph for Bore 75014 and Residual Rainfall Mass Curve for Peats Ridge Rainfall Station 109

4.35 Groundwater Hydrograph for Bore 75015~1 and Residual Rainfall Mass Curve for Peats Ridge Rainfall Station 109

4.36 Groundwater Hydrograph for Bore 75015~2 and Residual Rainfall Mass Curve for Peats Ridge Rainfall Station 110

4.37 Groundwater Hydrograph for Bore 75016 and Residual Rainfall Mass Curve for Peats Ridge Rainfall Station 110

4.38 Groundwater Hydrograph for Bore 75038~1 and Residual Rainfall Mass Curve for Peats Ridge Rainfall Station 111

4.39 Groundwater Hydrograph for Bore 75038~2 and Residual Rainfall Mass Curve for Peats Ridge Rainfall Station 111

5.1 Geological Map of the Study Area 113

5.2 General Section through the Narrabeen Group in the Wyong-Gosford area 117

5.3 Composite Groundwater Contour Map 121

5.4 Conceptual Model 122

6.1 General groundwater modelling process 124

6.2 Model Grid Mesh 127

6.3 Geological Cross-section 6-km North of Narara East-West 128

6.4 Geological cross-section along George Downes Dr through Kulnura North-South 128

6.5 Plan view and cross-section through the model layers 131

6.6 Soil landscape map 133

6.7 Vegetation cover map 134

6.8 Recharge Zones Map 135

6.9 Flow Gauge and Reach Location Map 137

6.10 Comparison of simulated baseflow with different hybase baseflow run (Ourimabah CK @ 211013 139

6.11 Boundary Condition for Layer 30 142

6.12 Boundary Condition for Layer 1 142

6.13 Boundary Condition for Layer 15 142

6.14 Drainage map with high order of stream lines 145

6.15 Drainage map with intermediate number of stream lines 146

6.16 Drainage map with low order of stream lines 146

6.17 Comparison Map between Observed and Simulated Water Level 148

6.18 Observed vs computed target values through the model layers 148

6.19 The calibrated Recharge Zones Map 150

6.20 Cumulative distribution function of water allocation 152

6.21 Cumulative distribution function for the extraction of bore's layer 152

6.22 Bore location map in layer 30 153

6.23 Bore location map in layer 29 153

6.24 Simulated vs. observed hydrograph for bore # GW064051 156

6.25 Simulated vs. observed hydrograph for bore # GW075009 156

6.26 Simulated vs. observed hydrograph for bore # GW075010 157

6.27 Simulated vs. observed hydrograph for bore # GW080167 157

6.28 Simulated vs. observed hydrograph for bore # GW075013~1 158

6.29 Simulated vs. observed hydrograph for bore # GW075013~2 158

6.30 Simulated vs. observed hydrograph for bore # GW075013~3 159

6.31 Simulated vs. observed hydrograph for bore # GW075014 159

6.32 Simulated vs. observed hydrograph for bore # GW075015~1 160

6.33 Simulated vs. observed hydrograph for bore # GW075015~2 160

6.34 Simulated vs. observed hydrograph for bore # GW080164 161

6.35 Simulated vs. observed hydrograph for bore # GW080163 161

6.36 Simulated vs. observed hydrograph for bore # GW075038~1 162

6.37 Simulated vs. observed hydrograph for bore # GW075038~2 162

6.38 Simulated vs. observed hydrograph for bore # GW075012~1 163

6.39 Simulated vs. observed hydrograph for bore # GW075012~1 163

6.40 Simulated vs. observed hydrograph for bore # GW075016 164

6.41 Simulated vs. observed hydrograph for bore # GW080168 164

6.42 Simulated vs. observed hydrograph for bore # GW080166 165

6.43 Simulated vs observed hydrograph for bore # GW080165 165

6.44 Sum of Square Residual for 20 DNR monitoring bores through the calibration period (Jan 1985 – Oct 2003) 166

6.45 Monitoring bores SSQR comparison between calibration and verification period 167

6.46 Scatter diagram of observed versus modelled head targets through the model layers 170

6.47 Simulated vs. observed baseflow in reach 400 172

6.48 Simulated vs. observed baseflow in reach 401 173

6.49 Simulated vs. observed baseflow in reach 201 173

6.50 Simulated vs. observed baseflow in reach 30 174

6.51 Simulated vs. observed baseflow in reach 301 174

6.52 Sensitivity to horizontal hydraulic conductivity (0.15 m/d) 177

6.53 Sensitivity to horizontal hydraulic conductivity (0.045 m/d) 177

6.54 Sensitivity to horizontal hydraulic conductivity (0.03 m/d) 178

6.55 Sensitivity to horizontal hydraulic conductivity (0.001m/d) 178

6.56 Sensitivity to vertical hydraulic conductivity (0.00012 m/d) 179

6.57 Sensitivity to vertical hydraulic conductivity (0.00004 m/d) 179

6.58 Sensitivity to vertical hydraulic conductivity (0.00005 m/d) 180

6.59 Sensitivity to specific yield (0.0175 m/d) 180

6.60 Sensitivity to specific yield (0.01 m/d) 181

6.61 Sensitivity to specific yield (0.0045 m/d) 181

6.62 Sensitivity to storage coefficient (0.000175 m/d) 182

6.63 Sensitivity to storage coefficient (0.0001 m/d) 182

6.64 Sensitivity to storage coefficient (0.000045 m/d) 183

6.65 Sensitivity to rainfall recharge zone 1 (13% rainfall) 183

6.66 Sensitivity to rainfall recharge zone 2-9 (5% rainfall) 184

6.67 Sensitivity to rainfall recharge zone 10 (10.5% rainfall) 184

6.68 Sensitivity to rainfall recharge zone 11 (14% rainfall) 185

6.69 Sensitivity to drain conductance 185

6.70 Monitoring bores SQR comparison between the baseline calibration with pumping and with no pumping scenario 186

6.71 The impact of scenario with no pumping on the hydrographs in bore GW064051 187

6.72 The impact of scenario with no pumping on the hydrographs in bore GW075010 188

7.1 Groundwater path lines resulting from particle tracking at top of Mangrove Mountain 190

7.2 Path lines and travel times through cross sectional view in Mangrove Mountain (Row 40, Column 30) 191

7.3 Groundwater path lines resulted from backward particle tracking at the drain cells 192

7.4 Path lines and travel times through cross sectional of the plan view for backward tracking into the drain cells 193

8.1 Schematic diagram for stream-aquifer interaction stages 195

8.2 Flowchart for coupling MODFLOW-SURFACT with GAMS using the response matrix approach 197

8.3 Bores location map 201

8.4 Hypothetical bores network in Ourimbah -Wyong catchments at layer 28 202

8.5 Optimal pumping cell location map in WSP area 206

8.6 Baseflow reduction versus hydraulic gradient reduction 210

8.7 Trade-off curve in WSP area 210

8.8 Optimal pumping cell location map in Brisbane-Water Catchment 213

8.9 Baseflow reduction versus hydraulic gradient reduction 216

8.10 Trade-off curve in Brisbane Water Catchment 216

8.11 Optimal pumping cell location map in Ourimbah catchment 219

8.12 Baseflow reduction versus hydraulic gradient reduction 222

8.13 Trade-off curves for Ourimbah catchment 223

8.14 Optimal pumping cell location map in Wyong catchment 225

8.15 Baseflow reduction versus hydraulic gradient reduction 228

8.16 Trade-off curves for Wyong catchment 229

8.17 Optimal pumping cell location map in all catchments 233

8.18 Optimal cell drawdown at the observation sites in all catchments under scenario 5 .235

8.19 Baseflow reduction versus hydraulic gradient reduction 239

8.20 Baseflow reduction versus hydraulic gradient reduction 239

8.21 Trade-off curves for the water sharing plan and the outside areas 240

8.22 Trade-off curve for the combination water sharing plan and the outside areas 241

8.23 Hypothetical Bores Network in Layer 1 242

8.24 Hypothetical Bores Network in Layer 15 243

8.25 Hypothetical Bores Network in Layer 30 244

8.26 Sustainable yield variation with the layers 245

8.27 Location map for the optimal hypothetical pumping cells at Layer 15 and change of the hydraulic gradient by 10% 249

8.28 Baseflow reduction versus hydraulic gradient reduction in Layer 15 250

8.29 Trade-off curve for hypothetical pumping cells at Layer 15 in water sharing plan area 251

8.30 Seasonal rainfall variations at Peats Ridge rainfall station 252

8.31 Cumulative distribution function for Gosford rainfall station 253

8.32 Cumulative distribution function for Gosford rainfall station 253

8.33 Optimal pumping cells location map in summer season 259

8.34 Optimal pumping cells location map in autumn season 260

8.35 Optimal pumping cells location map in winter season 261

8.36 Optimal pumping cells location map in spring season 262

8.37 Optimal pumping cells location map in dry condition 263

8.38 Optimal pumping cells location map in wet condition 264

8.39 Optimal cell drawdown at the observation sites in all catchments during summer season 266

8.40 Optimal cell drawdown at the observation sites in all catchments during autumn season 267

8.41 Optimal cell drawdown at the observation sites in all catchments during winter season 268

8.42 Optimal cell drawdown at the observation sites in all catchments during spring season 269

8.43 Optimal cell drawdown at the observation sites in all catchments during dry condition 270

8.44 Optimal cell drawdown at the observation sites in all catchments during wet condition 271

8.45 Trade-off curves for the water sharing plan under different climate conditions 279

8.46 Trade-off curves for the Wyong catchment under different climate conditions 279

8.47 Trade-off curves for the Ourimbah catchment under different climate conditions 280 conditions

8.48 Trade-off curves for the Brisbane catchment under different climate conditions 280

8.49 Trade-off curves for the combination water sharing plan and the outside areas under different climate conditions 281

8.50 Sustainable yield versus rainfall for each catchment in Kulnura-Mangrove area 282

8.51 Sustainable yield versus rainfall for all catchments in Kulnura-Mangrove area 282

LIST OF TABLES

Table	Title	Page
2.1	Estimation of annual recharge, water requirements and sustainable yield for each groundwater source	10
2.2	Daily flow sharing arrangements with Total Daily Extraction Limits TDEL ML/day	14
2.3	Daily flow sharing arrangements with Total Daily Extraction Limits TDEL ML/day	18
2.4	Previous applications of simulation-optimisation models on stream-aquifer system	72
3.1	Catchments description in the study area	77
4.1	Rainfall Stations in the study area	83
4.2	Statistical parameters for Gosford rainfall station from (July 1916 – May 2003)	84
4.3	Statistical parameters for Peats Ridge rainfall station from (Oct 1981 – August 2005)	86
4.4	Statistical parameters for Kulnura North rainfall station from (Oct 1959 – November 2001)	88
4.5	Statistical parameters for Laguna rainfall station from (April 1959 – April 2003)	90
4.6	Location of the stream flow gauges	98
4.7	Groundwater monitoring bores in Kulnura-Mangrove Mountain area	105
5.1	Stratigraphy of the study area	114
5.2	Section of Gosford Formation, Narrabeen Group, in Gosford district	118
6.1	Top and Bottom Elevation for each Layer	129
6.2	Flow Reach Description	136
6.3	Comparison of baseflow from two different hybase runs	139

6.4 Comparison between estimated and simulated baseflow in steady-state calibration 149

6.5 Comparison between estimated and simulated baseflow in the previous and current model 149

6.6 Groundwater budget of the model during the steady state calibration 149

6.7 Ranges of the calibrated hydraulic parameters 154

6.8 Number of measurements and SQR for each DNR monitoring bore through the calibration and verification processes 167

6.9 Calibration performance measures 169

6.10 Quantitative measures summary for the calibration performance in the regional complex Kulnura-Mangrove model 170

6.11 Global Water Budget at the end of stress period 250 171

6.12 SQR comparison with and without pumping for each monitoring bore 187

8.1 A typical GAMS program structure 199

8.2 The entitlement for SDF bores 200

8.3 Number of the hypothetical bores in the proposed layer 202

8.4 Optimisation model zone number characteristics 203

8.5 Sustainable yield in WSP area 205

8.6 Statistical summary for the optimal pumping bores in WSP at 10% hydraulic gradient reduction tolerance fraction 206

8.7 Statistical summary of the optimal pumping layer 207

8.8 Statistical summary for the drawdown at the observation sites at 10% hydraulic gradient reduction tolerance fraction 208

8.9 Statistical summary for the residual drawdown between MODFLOW-SURFACT and Response Matrix Optimisation at 10% hydraulic gradient reduction tolerance fraction 209

8.10 Baseflow reduction in WSP area 210

8.11 Sustainable yield in Brisbane Water Catchment 211

8.12 Statistical summary for the optimal pumping bores 212

8.13 Statistical summary for the drawdown at the observation sites at 10% hydraulic gradient reduction tolerance fraction 214

8.14 Statistical summary for the residual drawdown between MODFLOW-SURFACT and Response Matrix Optimisation at 10% hydraulic gradient reduction tolerance fraction 215

8.15 Baseflow reduction in Brisbane-Water Catchment 215

8.16 The sustainable yield in Ourimbah catchment 217

8.17 Statistical summary for the optimal pumping bores at 10% hydraulic gradient reduction tolerance fraction 218

8.18 Statistical summary of the candidate bores in Ourimbah Catchment at 10% hydraulic gradient reduction tolerance fraction 218

8.19 Statistical summary for the drawdown at the observation sites at 10% hydraulic gradient reduction tolerance fraction 220

8.20 Statistical summary for the residual drawdown between MODFLOW-SURFACT and Response Matrix Optimisation at 10% hydraulic gradient reduction tolerance fraction 221

8.21 Actual baseflow reduction in Ourimbah catchment 222

8.22 The sustainable yield in Wyong catchments 223

8.23 Statistical summary for the optimal pumping bores at 10% hydraulic gradient reduction tolerance fraction 224

8.24 Statistical summary of the candidate bores in Wyong Catchment at 10% hydraulic gradient reduction tolerance fraction 224

8.25 Statistical summary for the drawdown at the observation sites at 10% hydraulic gradient reduction tolerance fraction 225

8.26 Statistical summary for the residual drawdown between MODFLOW-SURFACT and Response Matrix Optimisation at 10% hydraulic gradient reduction tolerance fraction in Wyong Catchment 227

8.27 Actual baseflow reduction in Wyong catchment 228

8.28 Sustainable yield variations with hydraulic gradient reduction tolerance fraction in all catchments 230

8.29 Sustainable yields comparison with the previous scenarios for all catchments 231

8.30 Statistical summary for the optimal pumping bores at 10% hydraulic gradient reduction tolerance fraction 232

8.31 Statistical summary of the candidate bores in all catchments at 10% hydraulic gradient reduction tolerance fraction 232

8.32 Statistical summary for the drawdown at the observation sites at 10% hydraulic gradient reduction tolerance fraction 234

8.33 Statistical summary for the residual drawdown between MODFLOW-SURFACT and Response Matrix Optimisation at 10% hydraulic gradient reduction tolerance fraction in all areas 236

8.34 Actual baseflow reduction in all zones 238

8.35 Sustainable yield summary for all areas under scenario 5 240

8.36 35 Sustainable yield in WSP area 245

8.37 Statistical summary for the optimal pumping cells at 10% Hydraulic Gradient Reduction tolerance fraction and maximum pumping use = 240 m^3/d 246

8.38 Statistical summary for the drawdown at the observation sites at 10% Hydraulic Gradient Reduction tolerance fraction and maximum pumping use = 240 m^3/d 247

8.39 Variation in actual baseflow reduction with layers at 10% hydraulic gradient reduction 248

8.40 Sustainable yield in Layer 15 and at Maximum Pumping Use 240 m^3/d 248

8.41 Actual baseflow reduction in layer 15 250

8.42 Number of the pumping cells location within the catchment 254

8.43 Sustainable yield variations with hydraulic gradient reduction tolerance fraction in all catchments for each season 256

8.44 Sustainable yield variations with hydraulic gradient reduction tolerance fraction in all catchments for each season 257

8.45 Statistical summary for the optimal pumping bores at 10% hydraulic gradient reduction tolerance fraction 258

8.46 Statistical summary for the drawdown at the observation sites at 10% hydraulic gradient reduction tolerance fraction 265

8.47 Actual baseflow reduction in all zones during summer conditions 273

8.48 Actual baseflow reduction in all zones during autumn conditions 274

8.49 Actual baseflow reduction in all zones during winter conditions 275

8.50 Actual baseflow reduction in all zones during spring conditions 276

8.51 Actual baseflow reduction in all zones during dry conditions 277

8.52 Actual baseflow reduction in all zones during wet conditions 278

8.53 Sustainable yield for each catchment at 10% baseflow reduction under different climate conditions 281

LIST OF SYMBOLS

Symbol	**Description**	**Chapter**
GWCWA	Gosford Wyong Councils' Water Authority	1
DNR	Department of Natural Resources	1, 2, 6, 8, 9
KMMA	Kulnura – Mangrove Mountain Aquifer	9
DIPNR	Department of Infrastructure, Planning and Natural Resources	2
WSP	Water Sharing Plan	2, 8, 9
f_k	filtered quickflow response at the kth sampling instant	2
y_k	original streamflow at the kth sampling instant	2
y_{k-1}	original streamflow at the previous sampling instant to k	2
α	filter parameter representing the degree of attenuation	2
q_k	filtered baseflow response at the kth sampling instant	2
P	probability of a given flow being equalled or exceeded	2
m	rank for a discharge value	2
n	total number of streamflow readings	2
Q_t	streamflow at time t	2
Q_0	initial streamflow at the start of the recession segment	2
ΔQ	stream depletion flow rate	2
Q_w	constant flow rate abstracted at well from $t = 0$ to $t = \infty$	2
S	aquifer storage coefficient, specific yield or effective porosity	2
t	time	2, 6
l	the shortest distance between the well and stream edge	2
L	stream leakance that has a dimension of length	2

K	aquifer hydraulic conductivity	2
K'	streambed hydraulic conductivity	2
b'	thickness of semipervious layer	2
SDF	Stream Depletion Factor	2
λ	Hunt's leakage coefficient	2
M_a	number of active cells in the study area	2
a	cell index number	2
g_a	groundwater extraction by pumping in cell a	2
s_a	surface water diversion in cell a for use in cell a	2
$g_{a,k}$	groundwater extraction from cell a in time period k	2
$d_{a,k}$	streamflow diversion or reservoir release from reach e in time period k	2
Mp	total candidate number of cells from which groundwater withdrawal is optimised	2
Md	total number of potential stream diversion reaches	2
$C_{a,k}$	coefficients to perform minimisation, maximisation or economic optimisation on groundwater extraction	2
$C_{e,k}$	coefficients to perform minimisation, maximisation or economic optimisation on streamflow diversion	2
NW	total number of wells	2
ND_k	number of days in planning period k	2
TP	total number of planning periods	2
$Qw_{i,k}$	withdrawal rate at well i during planning period k	2
$Q_{j,t}$	streamflow at reach j during time period t	2
$Q^*_{j,t}$	minimum allowed streamflow at reach j in time t	2
$Qsd_{j,t}$	streamflow depletion at streamflow constraint site j in month t	2
$(Qsd_{j,t})max$	maximum rate of streamflow depletion allowed at site j in month t	2

	in month t	
$Qsd^{*}_{j,t}$	streamflow depletion at site j in month t in response to a unit withdrawal Qw^{*}_{i} at well i	2
$r_{j,i,t}$	response coefficients for each well and streamflow constraint site pair	2
$Qw_{i,t1}$ and $Qw_{i,t2}$	withdrawal rates at well i in month t1 and t2	2
$\alpha_{t1,2}$	ratio of total demand in month t1 to total demand in month t2	2
$S(k,n)$	drawdown at site k at the end on nth period	2
$\beta(k,j,n-i+1)$	response coefficients	2
$q(j,i)$	pulse pumping at site j and time i	2
M	total number of wells	2
n	total number of planning periods	2
k	observation site location	2
RM	Residual rainfall mass	4
$RAINmonth$	Total monthly rainfall in month A	4
$\overline{RAINmonth}$	Mean monthly rainfall for month A in all years	4
®	Automatic Water Level Recorder	4
AMG	Australian Map Grid	4
AHD	Australian Height Datum ≈Mean Sea Level	4
K_x, K_y, K_z	values of hydraulic conductivity along the x, y and z coordinate axes	6
K_{rw}	relative permeability, which is a function of water saturation	6
h	hydraulic head	6
W	volumetric flux per unit volume and represents sources and/or sinks of water per unit of time	6

S_w	degree of saturation of water, which is a function of the pressure head	6
Ss	specific storage of the porous material	6
S_y	specific yield	6
Q	flux into boundary cell	6
Hb	boundary head	6
Hm	head computed by model	6
C	boundary conductance	6
K_b	hydraulic conductivity of the boundary material	6
A	area of the boundary	6
B	thickness or width of boundary	6
SQR	Sum of Squares Residual	6
Wi	dimensionless weighting fraction (ranges from 0 to 1) for each i measurement in n samplings of data	6
hi	modelled head	6
Hi	measured head	6
Ri	Residual	6
SR	Sum of Residuals	6
MSR	Mean Sum of Residuals	6
SMSR	Scaled Mean Sum of Residuals	6
SSQ	Sum of SquaresResidual	6
MSSQ	Mean Sum of Squares	6
RMS	Root Mean Square	6
RMRS	Root Mean Fraction Square	6
SRMFS	Scaled Root Mean Fraction Square	6
SRMS	Scaled Root Mean Square	6
CD	Coefficent of Determination	6

w	total number of bores	8
p	total number of planning periods $p \geq 1$	8
$Q_{k,t}$	total amount of groundwater withdrawal at bore k and planning period t	8
DD (i,j)	Maximum allowed drawdown during pumping	8, A
$H_{OS}(i,j)$	Natural pre-pumping head at the observation site i,j	8
$H_{DB}(i,j)$	Head at the drain (stream) boundary i,j	8, A
T	hydraulic gradient reduction tolerance fraction	8, A
GAMS	General Algebraic Modelling System	8
SDF	Stock-Domestic-Farming bores	8
$H_{N(i,j)}$	Natural pre-pumping head at the observation site i,j	A
$H_{S(i,j)}$	Stressed during-pumping head at the observation site i,j	A
x	Distance between the observation site and the drain boundary	A
$\Delta H_{N(i,j)}$	Head difference between the observation site i,j at pre-pumping condition and the drain boundary i,j	A
$\Delta H_{S(i,j)}$	Head difference between the observation site i,j during pumping and the drain boundary i,j	A

ABSTRACT

The public water supply in the Gosford-Wyong area of New South Wales is reliant on streams that originate in elevated sandstone country. About half of the stream flow is believed to be baseflow from the sandstone aquifer system in the Kulnura - Mangrove Mountain area. At the same time as the population is growing steadily on the coast, there is increased demand for groundwater for horticultural, agricultural and industrial purposes along the sandstone ridges. Hence, good groundwater management is critical, to ensure that stream baseflow is not jeopardised.

A management model that couples a simulation model with an optimisation model has been developed for the Kulnura-Mangrove Mountain aquifer system to evaluate the trade-offs between increased aquifer yields and baseflow reduction. The project has been successful in developing trade-off curves for sustainable yield versus reduction in baseflow. It is believed that this is the first time that rigorous trade-off curves for sustainable yield have been developed for a stream-aquifer system in Australia.

The objectives of this research were to determine the sustainable yield(s) of the aquifer system in relation to extraction limits from both groundwater and surface water; to determine the magnitude, distribution and dynamics of baseflow to the streams which drain the Kulnura – Mangrove Mountain aquifer; to determine groundwater entitlement limits that would preserve baseflow to streams in order to facilitate groundwater allocation policy; and to explore how groundwater extraction limits would change for tolerable reductions in baseflow.

The simulation model is necessarily coarse, with 500 m spatial resolution, as replication of a very large regional aquifer was required. Given the wide variation in vertical relief in the area, approximately 400 metres, it was necessary to divide the vertical profile into 30 layers. Otherwise, it would not have been possible to track the many baseflow-receiving creeks that descend from high elevations to the sea.

The calibration results of the simulation model show that the model performs very well in representing the values and the patterns of groundwater level for both steady state and transient conditions, is able to reproduce large vertical hydraulic gradients between aquifer layers, and also replicates baseflow reasonably well.

The optimisation model was developed with the objective of preserving stream baseflow within tolerable limits while maximising the pumping rates from the aquifer system. Constraints were designed in terms of hydraulic gradient, with reduction tolerance ranges from 0.1 % to 10 %. Conversion from hydraulic gradient reduction to baseflow reduction was achieved by running reported optimal production patterns through the model in simulation mode. This work differs from that of previous researchers in not making a pre-emptive assumption of linearity between groundwater pumping and stream baseflow.

A very large optimisation problem has been solved in this study, consisting of up to 5700 decision variables and 8000 constraints. The study has been successful in generating trade-off curves that will provide a scientific basis for government / community decisions on responsible water allocation between computing users.