Frameworks for Assessing and Improving Urban Water Supply Security Planning under Climate Change

by

Fiona Laura Paton

BE (Hons); BSc

Thesis submitted to The University of Adelaide

School of Civil, Environmental & Mining Engineering in

fulfilment of the requirements for the degree of

Doctor of Philosophy

Submitted December 2013

Table of Contents

ABSTRACT ..... **V**

STATEMENT OF ORIGINALITY ..... **VII**

ACKNOWLEDGEMENTS ..... **IX**

LIST OF FIGURES ..... **XI**

LIST OF TABLES ..... **XV**

LIST OF ACRONYMS ..... **XIX**

1 INTRODUCTION **1**

1.1 RESEARCH OBJECTIVES 7
1.2 THESIS ORGANISATION 10

2 RELATIVE MAGNITUDES OF SOURCES OF UNCERTAINTY IN ASSESSING CLIMATE CHANGE IMPACTS ON WATER SUPPLY SECURITY FOR THE SOUTHERN ADELAIDE WATER SUPPLY SYSTEM (PAPER 1) **11**

2.1 INTRODUCTION 15
2.2 CASE STUDY 21
2.3 METHODS 23
2.3.1 Development of Rainfall Runoff (RRO) Model(s) *26*
2.3.2 Development of Climate Change Affected Rainfall and Evaporation Data *37*
2.3.3 Development of Water Supply System Model *43*
2.3.4 Water Supply Security Scenario Analysis *47*
2.4 RESULTS AND DISCUSSION 56
2.4.1 Relative Magnitudes of Sources of Uncertainty *56*
2.4.2 Identifying Critical Points in Time for Water Supply Security *66*
2.4.3 Water Supply Security Ranges *68*
2.5 SUMMARY AND CONCLUSIONS 69
ACKNOWLEDGEMENTS 72
APPENDICES SUPPORTING JOURNAL PAPER 1 72

3 INTEGRATED FRAMEWORK FOR ASSESSING URBAN WATER SUPPLY SECURITY OF SYSTEMS WITH NON-TRADITIONAL SOURCES UNDER CLIMATE CHANGE (PAPER 2) **73**

ABSTRACT 77
3.1 INTRODUCTION 77
3.2 INTEGRATED FRAMEWORK FOR ASSESSING URBAN WATER SUPPLY SECURITY OF SYSTEMS WITH NON-TRADITIONAL SOURCES UNDER CLIMATE CHANGE 80
3.2.1 Non-traditional Sources *81*
3.2.2 Climate Change Impact *84*
3.3 CASE STUDY 85
3.3.1 Objectives *87*
3.3.2 Water Supply Alternatives *89*
3.3.3 Simulation Model *91*
3.4 RESULTS AND DISCUSSION 106
3.4.1 Comparative Analysis of Alternatives *106*
3.4.2 Variation in Criteria Across the 252 scenarios *110*
3.4.3 Practical Management Implications *116*

3.5 Summary and Conclusions 116
Acknowledgements 119
Appendices Supporting Journal Paper 2 120

4 INCLUDING ADAPTATION AND MITIGATION RESPONSES TO CLIMATE CHANGE IN A MULTI-OBJECTIVE EVOLUTIONARY ALGORITHM FRAMEWORK FOR URBAN WATER SUPPLY SYSTEMS INCORPORATING GHG EMISSIONS (PAPER 3) 121

Abstract 125
4.1 Introduction 125
4.2 Incorporation of GHG emissions in the multiobjective optimisation of regional water supply systems 128
4.3 Case Study: The Southern Adelaide System 130
4.4 Methods 133
4.4.1 Objectives and Constraints 133
4.4.2 Water Supply Alternatives 133
4.4.3 Simulation Model 135
4.4.4 Objective Function Evaluation 138
4.4.5 Evaluation of Constraints 144
4.4.6 Optimisation 145
4.4.7 Post-Optimisation Robustness Assessment 146
4.5 Results 148
4.5.1 Optimisation 149
4.5.2 Post-Optimisation Robustness Assessment 154
4.5.3 Practical Management Implications 158
4.6 Summary and Conclusions 159
Acknowledgements 162
Appendices Supporting Journal Paper 3 162

5 THESIS CONCLUSIONS 163

5.1 Research Contributions 164
5.2 Additional Publications of this Research 168
5.3 Research Limitations 169
5.4 Recommendations for Future Work 172

APPENDIX A – JOURNAL PAPER 1 AS PUBLISHED IN *WATER RESOURCES RESEARCH* 175

APPENDIX B – INFORMATION ON THE CLIMATE-INDEPENDENT AND CLIMATE-DEPENDENT WATER SOURCES FOR THE CASE STUDY OF JOURNAL PAPER 2 203

B.1 Climate-Independent Supply Sources 205
B.2 Climate-Dependent Supply Sources 205
B.2.1 Impervious Catchments 205
B.2.2 Pervious Catchments 207

APPENDIX C – DETAILS OF THE DEVELOPMENT OF THE STOCHASTIC RAINFALL TIME SERIES FOR THE CASE STUDY OF JOURNAL PAPER 2 215

APPENDIX D – INFORMATION ON THE ECONOMIC COSTS DERIVED FOR THE CASE STUDY OF JOURNAL PAPER 2 219

D.1 Local Catchment Reservoirs 221
D.2 River Murray 221
D.3 Desalination Plant 222

D.4 HOUSEHOLD RAINWATER TANKS 223
D.5 HARVESTED STORMWATER 223

APPENDIX E – ECONOMIC COSTS OF WATER SUPPLY SOURCES FOR THE CASE STUDY OF JOURNAL PAPER 3 225

E.1 LOCAL CATCHMENT RESERVOIRS 227
E.2 RIVER MURRAY 228
E.3 DESALINATION 231
E.3.1 Capital Costs – Desalination Plant 231
E.3.2 Capital Costs – Transfer Pipeline 233
E.3.3 Ongoing Costs – Desalination Plant 236
E.3.4 Ongoing Costs – Transfer Pipeline 239
E.4 RAINWATER TANKS 239
E.4.1 Capital Costs 240
E.4.2 Ongoing Costs 240
E.5 STORMWATER SCHEMES 242
E.5.1 Capital Costs 242
E.5.2 Ongoing Costs 243

APPENDIX F – GHG EMISSIONS OF WATER SUPPLY SOURCES FOR THE CASE STUDY OF JOURNAL PAPER 3 ..245

F.1 LOCAL CATCHMENT RESERVOIRS 247
F.2 RIVER MURRAY 247
F.3 DESALINATION 248
F.3.1 Capital GHG Emissions – Desalination Plant 248
F.3.2 Capital GHG Emissions – Transfer Pipeline 249
F.3.3 Ongoing GHG Emissions – Desalination Plant 252
F.3.4 Ongoing GHG Emissions – Transfer Pipeline 254
F.4 RAINWATER TANKS 254
F.4.1 Capital GHG Emissions 254
F.4.2 Ongoing GHG Emissions 257
F.5 STORMWATER SCHEMES 259
F.5.1 Capital GHG Emissions 259
F.5.2 Ongoing GHG Emissions 262

APPENDIX G – BOXPLOTS ILLUSTRATING RESULTS FROM THE POST-OPTIMISATION ROBUSTNESS ASSESSMENT FOR THE CASE STUDY OF JOURNAL PAPER 3 265

REFERENCES 273

Abstract

There exist large uncertainties in projecting future climate and understanding how climate change projections relate to water supply. Non-traditional water sources (e.g., stormwater harvesting), which are emerging as adaptation options to augment stressed water supply systems, further complicate the simulation of these systems. However, in assessing a city's water supply security, there is no framework explicitly acknowledging and accounting for both the additional complexities and uncertainties associated with non-traditional water sources and climate change impacts. Furthermore, mitigation and adaptation measures to climate change should be considered. However, minimising GHG emissions (and thus considering mitigation) is likely to conflict with other objectives of water supply system planning. Hence, a multi-objective evolutionary algorithm (MOEA) approach is necessary to balance multiple objectives, as well as to efficiently search many feasible alternatives to find Pareto-optimal solutions. However, for cities, MOEA studies incorporating GHG emissions and thus focussing on both mitigating and adapting to climate change do not exist.

The main aim of this thesis is to develop methods for assessing and improving urban water supply security planning under climate change to better understand: (1) the relative magnitudes of uncertainty sources in assessing climate change impacts; (2) enhanced simulation complexity of non-traditional water sources and increased uncertainty of climate change impacts; and (3) adaptation and mitigation responses to climate change. Consequently, major contributions of this research include: (1) developing a scenario-based sensitivity analysis to understand the relative magnitudes of uncertainty sources in assessing the impacts of climate change on water supply systems; (2) developing a generalised framework for a city's water supply system that outlines the additional complexities due to the incorporation of non-traditional water sources and the additional uncertainties due to climate change impacts; and (3) incorporating GHG emissions as an objective function within a MOEA framework to take into consideration both adaptation and mitigation responses to climate change. Furthermore, while these frameworks could readily be applied to any

city, Adelaide's southern water supply system is used as a real-life case study to illustrate the practical management implications.

The methods developed in the thesis were found to be effective when applied to Adelaide's southern water supply system. Results indicate that studies analysing the impact of climate change on water supply security should consider uncertainties other than those associated with climate change and hydrological modelling, as these could have as great, if not greater, impacts on water supply security projections. Furthermore, trade-offs exist between cost and supply security for solutions that use desalination and harvested stormwater to augment water supply; however, use of rainwater tanks is undesirable, as they are an expensive source. In terms of the trade-off between economic cost and GHG emissions, the main drivers are the presence of rainwater tanks and the desalination plant – rainwater tanks are an expensive option, while desalination is a GHG emission intensive option. Consequently, while desalination may be a good adaptation option, other water sources may be better mitigation measures. Accounting for GHG emissions is thus important to ensure mitigation measures are considered.

Statement of Originality

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

I give consent to this copy of my thesis when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968.

The author acknowledges that copyright of published works contained within this thesis resides with the copyright holder(s) of those works.

I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library Search and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

Signed: . . . . . Date: . . . . . .

Acknowledgements

Foremost, I wish to thank my supervisors, Professor Holger Maier and Professor Graeme Dandy for their support, encouragement and guidance. Thank you for giving me the freedom to determine the direction this research project should take; for forcing me to grapple with problems and to challenge myself; for the flexibility in and understanding of my working hours and other commitments and interests; and, most importantly, for your effort, energy and dedication to this research.

Many people deserve thanks for their assistance in developing the computer programs for this thesis, none less than David Cresswell, who modified *WaterCress* on a number of occasions to suit the requirements of my research. Thank you also to Jeffrey Newman, a fellow postgraduate student and friend, who was always willing to help me with computer programming and Sri Srikanthan, who offered wonderful support for the *Stochastic Climate Library*. I would also like to thank Matthew Gibbs, Mark Thyer, Michael Leonard, Joanna Szemis and Leanne Webb for their input and support.

This research was made possible and enhanced by the financial support of the eWater CRC, which allowed me to purchase data, publish the papers presented herein and present my research at *MODSIM* (Cairns, 2009) and the *10th International Conference on Hydroinformatics* (Hamburg, 2012). I also acknowledge the G08 Universities Consortium for giving me the opportunity to partake at the *Climate Change: Science + Humanities* conference (Boston, 2010); and the Australia Korea Foundation, Australian Government, for giving me the opportunity to take part in the *Australia-Korea Next Generation Leaders Program: Sustainable Water Resource Management* (Korea, 2011). These conference experiences have influenced and contributed to the ideas developed in this thesis.

Finally, thank you to my family and friends, particularly Will, who have understood my study commitments and who have been compassionate and encouraging when I have doubted myself. Your continual support has enabled me to focus on finishing my doctoral studies.

List of Figures

FIGURE 1.1: HIERARCHY AND LINKAGE OF THE MAIN AIM, THREE MAJOR OBJECTIVES, AND NINE SUB-OBJECTIVES OF THIS RESEARCH. THE THREE JOURNAL PAPERS DEVELOPED TO ADDRESS THE MAIN AIM, AND EACH OF THE MAJOR OBJECTIVES AND SUB-OBJECTIVES, ARE ALSO DEPICTED. 9

FIGURE 2.1: MAP OF ADELAIDE'S SOUTHERN WATER SUPPLY SYSTEM, DETAILING RESERVOIRS, RESERVOIR CATCHMENTS, MAJOR RIVERS, PIPELINES, AND THE SOUTHERN SYSTEM DEMAND AREA. GAUGING STATIONS, RAINFALL STATIONS, MOUNT BOLD SUB-CATCHMENTS, AND ISOHEYTAL LINES THAT HAVE BEEN DEFINED FOR CALIBRATING RRO MODELS FOR EACH CATCHMENT ARE ALSO ILLUSTRATED. INSERT OF MAP OF AUSTRALIA HIGHLIGHTING LOCATION OF ADELAIDE. 22

FIGURE 2.2: FLOWCHART OF THE METHODOLOGY FOLLOWED FOR THE ADELAIDE SOUTHERN WATER SUPPLY SYSTEM CASE STUDY. 25

FIGURE 2.3: CUMULATIVE DISTRIBUTION FUNCTION (CDF) OF RELIABILITY (BASED ON 1000 STOCHASTIC RAINFALL TIME SERIES) OF ADELAIDE'S SOUTHERN WATER SUPPLY SYSTEM FOR DIFFERENT SRES SCENARIOS FOR 2020 AND 2050. 58

FIGURE 2.4: CDF OF RELIABILITY (BASED ON 1000 STOCHASTIC RAINFALL TIME SERIES) OF ADELAIDE'S SOUTHERN WATER SUPPLY SYSTEM FOR DIFFERENT GCMS FOR 2020. 58

FIGURE 2.5: CDF OF RELIABILITY (BASED ON 1000 STOCHASTIC RAINFALL TIME SERIES) OF ADELAIDE'S SOUTHERN WATER SUPPLY SYSTEM FOR DIFFERENT GCMS FOR 2050. 59

FIGURE 2.6: CDF OF RELIABILITY (BASED ON 1000 STOCHASTIC RAINFALL TIME SERIES) OF ADELAIDE'S SOUTHERN WATER SUPPLY SYSTEM FOR DIFFERENT DEMANDS FOR 2020 59

FIGURE 2.7: CDF OF RELIABILITY (BASED ON 1000 STOCHASTIC RAINFALL TIME SERIES) OF ADELAIDE'S SOUTHERN WATER SUPPLY SYSTEM FOR DIFFERENT DEMANDS FOR 2050 60

FIGURE 2.8: CHANGE IN MEDIAN RELIABILITY OVER THE PLANNING HORIZON OF ADELAIDE'S SOUTHERN WATER SUPPLY SYSTEM FOR DIFFERENT SRES SCENARIOS. 60

FIGURE 2.9: CHANGE IN MEDIAN RELIABILITY OVER THE PLANNING HORIZON OF ADELAIDE'S SOUTHERN WATER SUPPLY SYSTEM FOR DIFFERENT GCMS.....61

FIGURE 2.10: CHANGE IN MEDIAN RELIABILITY OVER THE PLANNING HORIZON OF ADELAIDE'S SOUTHERN WATER SUPPLY SYSTEM FOR DIFFERENT DEMANDS. 61

FIGURE 2.11: CDF OF RELIABILITY (BASED ON 1000 STOCHASTIC RAINFALL TIME SERIES) OF ADELAIDE'S SOUTHERN WATER SUPPLY SYSTEM FOR 2010 AND FOR THE BEST AND WORST CASES FOR 2020, 2030, 2040 AND 2050. 63

FIGURE 3.1: INTEGRATED FRAMEWORK FOR ASSESSING URBAN WATER SUPPLY SECURITY OF SYSTEMS WITH NON-TRADITIONAL SOURCES UNDER CLIMATE CHANGE, EXPLICITLY ILLUSTRATING THE ADDITIONAL COMPLEXITY AND UNCERTAINTY THAT NEED TO BE CONSIDERED 81

FIGURE 3.2: MAP OF THE EXISTING ADELAIDE SOUTHERN WATER SUPPLY SYSTEM, SHOWING RESERVOIRS, RESERVOIR CATCHMENTS, MAJOR RIVERS, PIPELINES, AND AN INDICATIVE SOUTHERN SYSTEM DEMAND AREA. THE PORT STANVAC DESALINATION PLANT AND THE TEN STORMWATER HARVESTING SCHEME CATCHMENTS USED IN MODELLING ARE ALSO SHOWN. INSET IS A MAP OF AUSTRALIA HIGHLIGHTING THE LOCATION OF ADELAIDE. 86

FIGURE 3.3: FLOWCHART OF THE GENERAL INTEGRATED FRAMEWORK APPLIED TO THE CASE STUDY BASED ON THE SOUTHERN ADELAIDE WATER SUPPLY SYSTEM. 88

FIGURE 3.4: MEDIAN AVERAGE RELIABILITY VERSUS ROBUSTNESS VERSUS MEDIAN AVERAGE PRESENT VALUE COST FOR THE NINE ALTERNATIVES FOR 2030 AND 2050 (DERIVED FROM 252 SCENARIOS). THE TWO SOLID LINES JOIN THE NON-DOMINATED SOLUTIONS ACROSS ALL THREE OBJECTIVES FOR 2030 AND 2050. 109

FIGURE 3.5: SCATTER PLOT OF AVERAGE RELIABILITY IN 2050 COMPARING THE DIFFERENT GCMS (TOP SECTION), DIFFERENT SRES SCENARIOS (MIDDLE SECTION) AND DIFFERENT DEMANDS (BOTTOM SECTION). WITHIN EACH SECTION AND FOR EACH DIFFERENT GCM, SRES SCENARIO OR DEMAND, THE ALTERNATIVES ARE ILLUSTRATED CONSECUTIVELY FROM ONE TO NINE IN COLUMNS FROM LEFT TO RIGHT, AS INDICATED AT THE TOP OF THE FIGURE. 111

FIGURE 3.6: SCATTER PLOT OF AVERAGE MAXIMUM DURATION OF FAILURE IN 2050 COMPARING THE DIFFERENT GCMS (TOP SECTION), DIFFERENT SRES SCENARIOS (MIDDLE SECTION) AND DIFFERENT DEMANDS (BOTTOM

section). Within each section and for each different GCM, SRES scenario or demand, the alternatives are illustrated consecutively from one to nine in columns from left to right, as indicated at the top of the figure. 112

Figure 3.7: Scatter plot of average maximum annual vulnerability in 2050 comparing the different GCMs (top section), different SRES scenarios (middle section) and different demands (bottom section). Within each section and for each different GCM, SRES scenario or demand, the alternatives are illustrated consecutively from one to nine in columns from left to right, as indicated at the top of the figure. 113

Figure 4.1: Map of the existing Adelaide southern water supply system, showing reservoirs, reservoir catchments, major rivers, pipelines, and an indicative southern system demand area (illustrated by grey shading). The Port Stanvac desalination plant and the ten southern water supply system stormwater harvesting scheme catchments are also shown. Inset is a map of Australia highlighting the location of Adelaide. 131

Figure 4.2: The Pareto front for the case study illustrating tradeoffs between (a) all three objectives; (b) average maximum annual vulnerability and GHG emissions; (c) GHG emissions and 2010 PV total system cost; and (d) average maximum annual vulnerability and 2010 NPV total system cost. The black triangles indicate the six solutions (numbered to correspond with Tables 4.6 and 4.7) selected for the post-optimisation robustness assessment. 150

Figure 4.3: Boxplot of average maximum annual vulnerability comparing the different GCMs (top section), different SRES scenarios (middle section), and different demands (bottom section). ... 157

Figure G. 1: Boxplot of average reliability comparing the different GCMs (top section), different SRES scenarios (middle section), and different demands (bottom section). 268

Figure G. 2: Boxplot of average maximum duration of failure comparing the different GCMs (top section), different SRES scenarios (middle section), and different demands (bottom section). ... 269

FIGURE G. 3: BOXPLOT OF 2010 NPV TOTAL SYSTEM COST COMPARING THE DIFFERENT GCMS (TOP SECTION), DIFFERENT SRES SCENARIOS (MIDDLE SECTION), AND DIFFERENT DEMANDS (BOTTOM SECTION). 270

FIGURE G. 4: BOXPLOT OF TOTAL SYSTEM GHG EMISSIONS COMPARING THE DIFFERENT GCMS (TOP SECTION), DIFFERENT SRES SCENARIOS (MIDDLE SECTION), AND DIFFERENT DEMANDS (BOTTOM SECTION). 271

List of Tables

TABLE 2.1: GAUGING STATION DATA FOR EACH CATCHMENT. 27

TABLE 2.2: RAINFALL STATION DATA FOR EACH CATCHMENT. 30

TABLE 2.3: AVERAGE MONTHLY EVAPORATION FOR CLIMATE DATA STATIONS. 31

TABLE 2.4: CALIBRATION AND VALIDATION PERIODS FOR CATCHMENTS AND SUB-CATCHMENTS. 31

TABLE 2.5: ROOT MEAN SQUARED ERROR (RMSE), NASH-SUTCLIFFE (NS), RATIO OF RMSE TO STANDARD DEVIATION (SD), AND AVERAGE OBSERVED AND MODELLED FLOWS FOR THE CALIBRATION AND VALIDATION PERIODS OF THE WC1 MODELS FOR THE MYPONGA, MOUNT BOLD (SIMPLE), MOUNT BOLD (COMPLEX), AND CLARENDON WEIR CATCHMENTS. 35

TABLE 2.6: PARAMETER VALUES FOR THE WC1 RRO MODELS FOR EACH OF THE CATCHMENTS. 36

TABLE 2.7: IMPORTANT ANNUAL STATISTICAL PROPERTIES OF THE HISTORICAL AND GENERATED RAINFALL TIME SERIES. 42

TABLE 2.8: MONTHLY MOUNT BOLD RESERVOIR LEVELS (AS A PERCENTAGE OF FULL CAPACITY) THAT TRIGGER USE OF RIVER MURRAY SUPPLY. 45

TABLE 2.9: PROPERTIES OF MOUNT BOLD, HAPPY VALLEY AND MYPONGA RESERVOIRS. 46

TABLE 2.10: MONTHLY OUTDOOR WATER USE AS A PERCENTAGE OF TOTAL ANNUAL OUTDOOR WATER USE [*BARTON*, 2005]. 48

TABLE 2.11: DEMAND SCENARIO OPTIONS. 51

TABLE 2.12: SCENARIO OPTIONS DEFINED FOR THE CASE STUDY OF ADELAIDE'S SOUTHERN WATER SUPPLY SYSTEM 53

TABLE 2.13: PROBABILITY OF EXCEEDANCE SUMMARY FOR RELIABILITY FOR YEARS 2030 AND 2040 FOR EACH OF THE 16 SCENARIOS DETAILED IN TABLE 2.12 62

TABLE 2.14: RANGE IN MEDIAN RELIABILITY CAUSED BY UNCERTAINTY IN SRES SCENARIO, GCM AND DEMAND FOR 2020, 2030, 2040 AND 2050 FOR EACH OF THE 16 SCENARIOS IN TABLE 2.12. 62

TABLE 3.1: ALTERNATIVES CONSIDERED FOR ADELAIDE'S SOUTHERN WATER SUPPLY SYSTEM CONFIGURATION 90

TABLE 3.2: DEMAND TYPE, WATER SOURCE, AND 2010 INDIVIDUAL PER CAPITA CONSUMPTION FOR THE FIVE DEMAND CATEGORIES DEFINED FOR THE ADELAIDE SOUTHERN SYSTEM CASE STUDY 93

TABLE 3.3: MONTHLY RESIDENTIAL GARDEN WATER DEMAND AS A PERCENTAGE OF TOTAL ANNUAL RESIDENTIAL GARDEN WATER DEMAND [*BARTON*, 2005] 93

TABLE 3.4: PROPERTIES AND CONSTRAINTS OF RESERVOIRS, WETLANDS, AND AQUIFERS FOR THE SOUTHERN WATER SUPPLY SYSTEM MODEL 97

TABLE 3.5: DEMAND SCENARIO OPTIONS 99

TABLE 3.6: SUMMARY OF ECONOMIC COST ESTIMATIONS FOR THE ADELAIDE'S SOUTHERN SYSTEM WATER SUPPLY SOURCES 105

TABLE 3.7: MEDIAN VALUES (BASED ON 252 SCENARIOS) FOR AVERAGE RELIABILITY, AVERAGE MAXIMUM RESILIENCE, AVERAGE MAXIMUM ANNUAL VULNERABILITY EXPRESSED AS A PERCENTAGE OF DEMAND AND NET PRESENT VALUE OF TOTAL SYSTEM COST, AND ROBUSTNESS FOR THE NINE ALTERNATIVES IN 2030 AND 2050. 107

TABLE 4.1: VALUES FOR OPTIONS OF SUPPLY SOURCE AUGMENTATION AND SUPPLY SYSTEM OPERATION DEFINED FOR THE CASE STUDY 134

TABLE 4.2: DEMAND TYPE AND WATER SOURCE FOR THE FIVE DEMAND CATEGORIES DEFINED FOR THE ADELAIDE SOUTHERN SYSTEM CASE STUDY 137

TABLE 4.3: ECONOMIC COST SUMMARY FOR DIFFERENT WATER SUPPLY SOURCES 140

TABLE 4.4: DEMAND SCENARIO OPTIONS 148

TABLE 4.5: MEDIAN UNIT COSTS AND GHG EMISSIONS (INCLUDES BOTH CAPITAL AND OPERATIONAL COSTS AND GHG EMISSIONS) DERIVED FROM THE 792 PARETO OPTIMAL SOLUTIONS FOR THE DIFFERENT SUPPLY SOURCES 151

TABLE 4.6: VALUES FOR THE CAPITAL DECISION VARIABLES FOR THE SIX SOLUTIONS SELECTED FOR THE POST-OPTIMISATION ROBUSTNESS ASSESSMENT 155

TABLE 4.7: CRITERIA VALUES FOR THE SIX SOLUTIONS NOMINATED FOR THE POST-OPTIMISATION ROBUSTNESS ASSESSMENT 155

TABLE B. 1: ROOF AND PAVEMENT AREAS FOR ADELAIDE'S SOUTHERN WATER SUPPLY SYSTEM FOR HOUSEHOLD RAINWATER TANKS AND THE SIX STORMWATER HARVESTING SCHEMES 206

TABLE B. 2: GAUGING STATION DATA FOR THE LOCAL CATCHMENT RESERVOIR AND HARVESTED STORMWATER CATCHMENTS 208

TABLE B. 3: WC1 MODEL PARAMETERS FOR THE PERVIOUS CATCHMENTS FOR THE SOUTHERN WATER SUPPLY SYSTEM MODEL 211

TABLE B. 4: PERFORMANCE CRITERIA FOR THE CALIBRATION AND VALIDATION OF PERVIOUS CATCHMENTS 214

TABLE E. 1: INDICATIVE COSTS FOR THE POWER AND CHEMICAL COSTS OF TREATING WATER AT THE WTPS AND THE COST OF LABOUR 229

TABLE E. 2: CAPITAL COST INFORMATION FOR WATER TREATMENT PLANTS BUILT IN SOUTH AUSTRALIA USED TO CALCULATE THE CAPITAL COST OF THE HAPPY VALLEY WTP 230

TABLE E. 3: CAPITAL COSTS FOR THE DIFFERENT DESALINATION PLANT CAPACITIES 232

TABLE E. 4: CAPITAL COSTS AND CURRENT AND EXPANSION CAPACITIES OF REVERSE OSMOSIS DESALINATION PLANTS RECENTLY BUILT IN AUSTRALIAN CITIES 232

TABLE E. 5: DESIGN FEATURES OF THE TRANSFER PIPELINE FOR EACH POTENTIAL PORT STANVAC DESALINATION PLANT CAPACITY 234

TABLE E. 6: COST BREAKDOWN FOR TRANSFER PIPELINE FOR EACH POTENTIAL PORT STANVAC DESALINATION PLANT CAPACITY 235

TABLE E. 7: OPERATIONAL COST INFORMATION FOR RO DESALINATION PLANTS 237

TABLE E. 8: OPERATIONAL COST BREAKDOWN FOR THE DIFFERENT CAPACITY DESALINATION PLANTS OF THE CASE STUDY 238

TABLE E. 9: COST OF TANK, DELIVERY, INSTALLATION AND DOLOMITE BASE FOR DIFFERENT SIZED RAINWATER TANKS 241

TABLE E. 10: COST OF PUMP AND PLUMBING FOR DIFFERENT HARVESTED RAINWATER END USES 241

TABLE E. 11: ENERGY INTENSITIES OF THE PUMP FOR DIFFERENT HARVESTED RAINWATER END USES 243

TABLE E. 12: CAPITAL COST SUMMARY FOR THE STORMWATER HARVESTING SCHEMES.....244

TABLE F. 1: ESTIMATED GHG EMISSIONS FOR A 100GL/YR DESALINATION PLANT BASED ON VALUES REPORTED BY *SA WATER* [2009] FOR THE ADELAIDE DESALINATION PLANT.....249

TABLE F. 2: CAPITAL GHG EMISSIONS FOR THE DIFFERENT DESALINATION PLANT CAPACITIES.....250

TABLE F. 3: PIPE DIAMETER, CEMENT AND STEEL THICKNESS AND VOLUMES OF MATERIALS AND RESULTING GHG EMISSIONS FOR THE 12KM MSCL TRANSFER PIPELINE DESIGNED FOR THE DIFFERENT DESALINATION PLANT CAPACITIES 251

TABLE F. 4: ONGOING GHG EMISSION BREAKDOWN FOR THE MAJOR DESALINATION OPERATING PROCESSES.....253

TABLE F. 5: GHG EMISSIONS ATTRIBUTED TO POWER, CHEMICALS, AND MEMBRANES FOR EACH DESALINATION PLANT CAPACITY (ASSUMING THE PLANT OPERATED AT FULL CAPACITY).....253

TABLE F. 6: MAXIMUM PUMP POWER AND MAXIMUM ANNUAL GHG EMISSIONS FOR THE TRANSFER PIPELINE 255

TABLE F. 7: DIAMETER, HEIGHT, VOLUME OF HDPE AND GHG EMISSIONS FOR DIFFERENT SIZED RAINWATER TANKS256

TABLE F. 8: LENGTH, VOLUME OF, AND GHG EMISSIONS ASSOCIATED WITH THE PVC PIPE FOR THE DIFFERENT ROOF CONNECTIVITIES.....258

TABLE F. 9: ENERGY INTENSITIES OF THE PUMP FOR DIFFERENT HARVESTED RAINWATER END USES 258

TABLE F. 10: WETLAND AREA, MASS OF CONCRETE AND STEEL ESTIMATED FOR EACH WETLAND, AND CORRESPONDING GHG EMISSIONS.....260

TABLE F. 11: MATERIALS AND CONSTRUCTION GHG EMISSIONS FOR THE ASR WELLS 260

TABLE F. 12: WETLAND AND ASR CONSTRUCTION GHG EMISSIONS FOR EACH STORMWATER SCHEME 261

TABLE F. 13: ESTIMATED LENGTH OF PIPELINES FOR THE STORMWATER SCHEMES' DISTRIBUTION NETWORK, THE CORRESPONDING VOLUME OF HDPE REQUIRED AND THE RESULTING GHG EMISSIONS ASSOCIATED WITH THE HDPE AND INSTALLATION OF THE PIPELINE 262

TABLE F. 14: SUMMARY OF CAPITAL GHG EMISSIONS FOR THE STORMWATER HARVESTING SCHEMES.....263

List of Acronyms

AIC	Akaike Information Criterion
ASR	Aquifer Storage and Recovery
BoM	Bureau of Meteorology
Cdf	Cumulative distribution function
CFF	Climate Futures Framework
CMIP	Coupled Model Intercomparison Project
CRC	Cooperative Research Centre
CSIRO	(Australian) Commonwealth Scientific and Industrial Research Organisation
ENSO	El Niño Southern Oscillation
FFCEF	Full Fuel Cycle Emissions Factor
GA	Genetic Algorithm
GCM	General Circulation Model
GHG	Greenhouse Gas Emissions
HDPE	High Density Polyethylene
IPCC	Intergovernmental Panel on Climate Change
Lcd	Litres per capita per day
LOS	Level Of Service
MBO	Murray Bridge-Onkaparinga
MOEA	Multi-Objective Evolutionary Algorithm
MOGA	Multi-Objective Genetic Algorithm
MOO	Multi-Objective Optimisation
MSCL	Mild Steel Cement Lined
NS	Nash-Sutcliffe
NSGA-II	Non-Sorted Genetic Algorithm 2
PPD	Patched Point Dataset
PSHV	Port Stanvac Happy Valley
PV	Present Value
RCF	Representative Climate Future
RDM	Robust Decision Making
RMSE	Root Mean Squared Error
RRO	Rainfall-Runoff Model
SCL	Stochastic Climate Library
SD	Standard Deviation
SRES	Special Report on Emissions Scenarios
UWOT	Urban Water Optioneering Tool
UWSS	Urban Water Supply System
WaterCress	Water – Community Resource Evaluation and Simulation System
WSMGA	Water System Multi-objective Genetic Algorithm
WTP	Water Treatment Plant