



THE UNIVERSITY
of ADELAIDE

An adaptive multi-objective framework for the scheduling of
environmental flow management alternatives using ant colony
optimization

Joanna Margaret Szemis

BEng (Civil & Structural) Hons

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

Copyright © June 2014.

Contents

Contents	i
Abstract	vii
Statement of Originality	ix
Acknowledgements	xi
List of Figures	xiii
List of Tables	xvii
1 Introduction	1
1.1 Research Objectives	4
1.2 Thesis Overview	8
2 A framework for using ant colony optimization to schedule environmental flow management alternatives for rivers, wetlands, and floodplains (Paper 1)	11
2.1 Introduction	16
2.2 Framework for the Optimal Scheduling of Environmental Flow Management Alternatives	21
2.2.1 Problem Formulation	22
2.2.2 Selection of Objective Function and Constraints	25
2.2.3 Environmental Flow Management Schedules Development	28

2.2.4	Calculation of Objective Function and Optimization	29
2.3	Proposed Ant Colony Optimization for the Scheduling of Environmental Flow Management Alternatives	30
2.3.1	Problem Representation	32
2.3.2	Ant Colony Optimization Algorithm	33
2.3.3	Dynamic Constraint Adjustment	36
2.4	Case Study.....	37
2.4.1	Problem Formulation	38
2.4.1.1	Identification of Ecological Assets and Indicators ...	38
2.4.1.2	Planning Horizon and Time Interval.....	44
2.4.1.3	Management Alternatives and Suboptions	44
2.4.2	Objective Function and Constraints	45
2.4.3	Calculate Objective Function	47
2.4.3.1	Wetland Hydrology Model.....	47
2.4.3.2	Floodplain Hydrology Model	48
2.4.4	ACO Algorithm	48
2.5	Analysis Conducted.....	49
2.5.1	Validation of Optimization Framework	50
2.5.2	Determination of Optimal Trade-Offs Between Recruitment and Maintenance Scores for Different Flow Allocations	54
2.5.3	Determination of Optimal Trade-Off Between Flora and Fauna Ecological Response.....	55
2.5.4	Determination of Optimal EFMA Schedules as a Result of Hydrograph Inversion	56
2.6	Results and Discussion	57
2.6.1	Validation of Optimization Framework	57
2.6.2	Determination of Optimal Trade-Offs Between Recruitment and Maintenance Scores for Different Flow Allocations	62
2.6.3	Determination of the Optimal Trade-Off Between Flora and Fauna Ecological Response.....	67

2.6.4	Determination of Optimal EFMA Schedules as a Result of Hydrograph Inversion	70
2.7	Summary and Conclusion	73
3	A multi-objective ant colony optimization approach for scheduling environmental flow management alternatives with application to the River Murray, Australia (Paper 2)	77
3.1	Introduction	82
3.2	Case Study: River Murray in South Australia	85
3.3	Methodology.....	88
3.3.1	Problem Formulation.....	90
3.3.1.1	Identification of assets and ecological indicators	90
3.3.1.2	Selection of Planning Horizon and Time Interval.....	92
3.3.1.3	Determination of Management Alternatives and Suboptions	92
3.3.2	Identification of Objective Functions and Constraints.....	93
3.3.3	Development of Management Schedules	97
3.3.4	Calculation of Objective Functions.....	99
3.3.5	Multi-objective Optimization	102
3.3.5.1	Pareto Ant Colony Optimization.....	105
3.3.5.2	COMPETants.....	105
3.3.5.3	m-ACO variant 3 (m-ACO ₃).....	106
3.3.5.4	Fitness Function	107
3.3.5.5	Comparison of Performance of Multi-objective Optimisation Algorithms	109
3.4	Analyses Conducted.....	114
3.4.1	Impact of upstream flow constraints	115
3.4.1.1	Trade-offs between environmental flow allocation and total ecological response.....	115

3.4.1.2	Trade-off between environmental flow allocation, wetland ecological response and floodplain ecological response	116
3.4.2	Impact of additional regulators	118
3.5	Results and Discussion	119
3.5.1	Impact of upstream flow constraints	120
3.5.1.1	Impact on Optimal Trade-off Curve	120
3.5.1.2	Impact on Effectiveness of Various Environmental Flow Allocations	128
3.5.2	Impact of Additional Regulators	129
3.5.2.1	Impact on Optimal Trade-off Curve	129
3.5.2.2	Impact on Effectiveness of Various Environmental Flow Allocations	131
3.5.3	Limitations	133
3.6	Summary and Conclusion	134
4	An adaptive ant colony optimization framework for scheduling environmental flow management alternatives under varied environmental water availability conditions (Paper 3)	137
4.1	Introduction	142
4.2	Proposed Adaptive Optimization Approach for the Optimal Scheduling of Environmental Flow Management Alternatives	145
4.3	Methodology	150
4.3.1	Case Study	150
4.3.2	Problem Formulation	152
4.3.2.1	Specification of Ecological Assets and Indicators	152
4.3.2.2	Identification of Planning Horizon, Time and Update Intervals	154
4.3.2.3	Selection of Management Alternatives and Suboptions	155
4.3.3	Specification of Objective Function and Constraints	156

4.3.4	Forecasting of Future Environmental Water Allocation ..	159
4.3.5	Development of Environmental Flow Management Schedules.....	164
4.3.6	Calculation of Objective Function and Assessment of Constraints.....	165
4.3.7	Optimization	167
4.3.8	Updating of EFMA Schedule	171
4.4	Analysis Conducted	171
4.4.1	Effectiveness of Using Optimal EFMA Scheduling	172
4.4.2	Effectiveness of Adaptive Optimization Approach	173
4.4.3	Effectiveness of Minimization of Differences between Successive Schedules.....	173
4.4.4	Effectiveness of ANN Forecasting Model.....	173
4.5	Results and Discussion.....	174
4.5.1	Effectiveness of using Optimal EFMA Scheduling	174
4.5.2	Effectiveness of Adaptive Optimization Approach	175
4.5.3	Effectiveness of Minimization of Differences between Successive Schedules.....	179
4.5.4	Effectiveness of Minimization of Differences between Successive Schedules.....	180
4.6	Conclusions and Recommendations	180
5	Conclusions	183
5.1	Research Contribution.....	184
5.2	Limitations	187
5.3	Future Work	188
	References	191
	Appendix A	205

Appendix B	227
-------------------------	-----

Abstract

Rivers and their adjacent wetlands and floodplains worldwide have been altered or have vanished as a result of river regulation and development (such as dams, locks and weirs), as well as water over-allocation. In recent years, environmental flow management has been suggested as a means to mitigate these negative impacts. One approach in order to do this is through the scheduling of environmental flow management alternatives (EFMAs), such as reservoir releases and the operation of wetland regulators. However, this is not an easy task for the following reasons: (i) there are generally many wetlands and floodplains in any particular river system, all containing a wide range of biota that have different flow requirements; (ii) there is generally limited water allocated for environmental purposes, since there are multiple users (e.g. irrigation, domestic), all competing for the same water source; (iii) the schedules are generally developed over multiple years; and (iv) there are multiple competing objectives and constraints that need to be considered. This problem therefore lends itself to be formulated as an optimization problem, where the aim is to maximise the ecological integrity of the system, while also considering humans needs and the constraints of the system.

In this thesis, a generic adaptive multi-objective optimization framework for determining the optimal schedule of EFMA for rivers and their associated wetlands and floodplains is developed and tested. In order to achieve this, ant colony optimization algorithms are selected, since they can take into account the conditional dependencies and sequential nature of the scheduling problem explicitly. This is possible, as the solution space can be represented by a graph structure that can be adjusted dynamically based on the choices made at

previous points in the decision graph, thereby reducing the size of the decision space and increasing the proportion of feasible solutions. This is not possible when most other metaheuristics are used. In addition to this, the framework is adaptive and able to incorporate forecasts of environmental water allocation, such that the environmental water can be used most efficiently in order to maximize ecological response.

The major research contributions are presented in three journal publications. Firstly, the initial single-objective formulation of the optimisation framework, which incorporates the temporal dependencies associated with the scheduling of EFMA is presented and validated using a hypothetical case study. The framework is then extended to incorporate multiple objectives and applied to a river section in the South Australian River Murray, so that the trade-off between the ecological response and environmental water allocation can be examined. Finally the framework is further extended to incorporate adaptive features by using forecasts of environmental water allocation in the development of EFMA schedules, as well as an additional objective which aims to minimise the number of differences of EFMA schedules developed at subsequent time steps. Thus the framework provides valuable insight to managers into the EFMA scheduling problem, as it can be applied to investigate a wide variety of problems, such as investigating the likely ecological benefit gained from an increase in environmental allocation, the impact of system constraints on ecological response and the potential advantages of investment in additional infrastructure.

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

Firstly, I would like to thank my supervisors, Prof Holger Maier and Prof Graeme Dandy, for their supervision, support and encouragement over the course of my PhD candidature. I would particularly like to thank Prof Holger Maier for his continual enthusiasm, vision and determination for my research to succeed. I am also grateful to Prof Graeme Dandy for his constant motivation and scientific insight into my research. Without their guidance, I would have never finished my PhD research. Thank You!

I would also like to thank Tumi Bjornsson and Richard Thompson, who went out of their way and happily provided the vital data for this PhD research. If it wasn't for these data, this research would have been very difficult to finish.

I very grateful to my fellow PhD students Fiona Paton, Jeffery Newman and Eva Beh for their friendship, encouragement, help and enjoyable discussions, which made the PhD experience less daunting than it would have been alone. Many thanks also to staff and other PhD students in the School of Civil, Environmental and Mining Engineering who have helped me throughout my PhD.

I would also like to thank my mother, Margaret, for her unwavering support through this rollercoaster ride, as well as my father, Olgierd, who every week would call and motivate me to press on. I would like to thank Andrew and Lizzie Szemis and Donna Krieg, who would be there to take my mind off things related to my research.

Finally, and most importantly, I like to thank God, who put me on this journey, which I would never have thought in million years I would be on. It has been definitely challenging and at times questionable, but in the end very rewarding.

List of Figures

Figure 1.1: Research objectives and their hierarchy. Objectives are denoted by the superscript numbers in each of the flowchart boxes..... 7

Figure 2.1: Representation of the optimal scheduling of environmental flow management alternative 21

Figure 2.2: Steps in formulation of environmental flow management schedule optimization problem. The river reaches, wetlands, and floodplains are defined as H_i , and i ranges from 1 to q . The ecological indicators, $E_{i,r}$, where r ranges from 1 to s , are specified for each H_i . The planning horizon is defined as Y_v , where v ranges from 1 to v years, while the time interval, t , ranges from 1 to the final time interval, T . The number of management alternatives, M_a , ranges from 1 to h 23

Figure 2.3: Environmental flow management schedule development, where the number of management alternative, M_a , ranges from 1 to h . The time step, t , ranges from 1 to T months, while $M_{a,m}$ and $M_{a,d}$ are the magnitude and duration suboptions for each M_a and d corresponds to the duration of $M_{a,d}$ 29

Figure 2.4: Example of an EFMA schedule graph for flow releases (in gegaliters (GL))..... 33

Figure 2.5: Steps in ant colony optimization algorithm 34

Figure 2.6: Example of an environmental flow management schedule decision tree graph using dynamic constraints 36

Figure 2.7: Layout of case study 38

Figure 2.8: MFAT response curves adapted from *Young et al.* (2003) and the Inside MFAT website (<http://www2.mdbc.gov.au/livingmurray/mfat/index.htm>) 42

Figure 2.9: Environmental flow management schedule development using the heuristic approach..... 53

Figure 2.10: Monthly flow releases for heuristic and ACO management schedule for Investigation 6. 59

Figure 2.11: ACO management schedule for Investigation 3.	62
Figure 2.12: Optimal trade-offs between MFAT recruitment and maintenance scores for 500–12,000 GL allocations.....	63
Figure 2.13: Monthly flow releases for the three points along the 10,000 GL allocation trade-off.....	66
Figure 2.14: Flow releases for Investigations 10 and 11	69
Figure 3.1: Map of case study area adapted from Murray-Darling Basin Authority website (http://www.mdba.gov.au/river-data/spatial-data-services/spatial-information).....	87
Figure 3.2: Steps in optimization framework	89
Figure 3.3: Example of an EFMA schedule graph for environmental flow releases (In Gigalitres (GL)) incorporating dynamic constraints.....	98
Figure 3.4: Traditional Ant Colony Optimization Procedure.....	104
Figure 3.5: Hypervolume convergence for each multi-objective ACO algorithm when $h < 4$	110
Figure 3.6: Comparison of PACOA, COMPETants and m-ACO ₃ using EAF differences plots.....	113
Figure 3.7: Optimal trade-offs between environmental flow allocation (GL/5yr) and MFAT score for Investigations 1-5.....	121
Figure 3.8: Optimal trade-offs between environmental water allocation (GL/5yr) and MFAT score for Investigations 2 (i.e. 1650 GL/month) and 5 (i.e. 3,000GL/month).....	125
Figure 3.9: Optimal trade-off between environmental water allocation (EWA (100 GL/5yr)) and the wetland and floodplain MFAT score for Investigation 6	127
Figure 3.10: Optimal trade-offs between environmental flow allocation and MFAT score for Investigations 1, 3 and 7-10.....	130
Figure 4.1: Steps in Proposed Adaptive Optimization Framework	147
Figure 4.2: Map of case study area (adapted from Murray-Darling Basin Authority website, http://www.mdba.gov.au/river-data/spatial-data-services/spatial-information)	151

Figure 4.3: Graph of Training Data Standardized Residuals for the ANN 1 model.	163
Figure 4.4: Example of an EFMA Schedule Graph for Environmental Flow Releases (In Gigalitres (GL)) incorporating Dynamic Constraints.....	165
Figure 4.5: Pareto Ant Colony Optimization Algorithm Procedure	168
Figure 4.6: Average Annual MFAT Scores Achieved for each Method and Actual Data Between the Years 1983-2003.....	174
Figure 4.7: Actual Flows at the South Australian Border	174
Figure 4.8: Average Annual MFAT Scores Achieved for Method1 and 2 for the Years 1983-2003.....	176
Figure 4.9: Average Annual MFAT Scores for Floodplain and Wetland Flora Achieved for Methods 1 and 2 Between the Years 1983-2003	179
Figure 4.10: Trade-off Curves Developed using Method 2 for the 1 st Year (1983-1984), 10 th Year (1992-1993) and 20 th Year (2002-2003)	180

List of Tables

Table 2.1: Wetland and Floodplain Specifications	40
Table 2.2: MAX-MIN Ant Systems Parameters	49
Table 2.3: Details of Each Study and Corresponding Objective	50
Table 2.4: Details of the Investigations used in each Study	50
Table 2.5: Details of the 6 Investigations used for Developing Heuristic and Optimization Based Management Schedules.....	52
Table 2.6: Seasonal Environmental Flow Allocation used in Investigation 12	57
Table 2.7: Heuristic and ACO Management Schedule Results for Investigations 1 to 6.....	58
Table 2.8: Difference in Annual MFAT Scores between Management Schedules obtained using ACO and Heuristic Approaches for Investigation 6	59
Table 2.9: Annual Recruitment and Maintenance Scores for the Three 10,000 Water Allocation Investigations.....	66
Table 2.10: Maintenance and Recruitment Scores for Investigations 10 and 11	68
Table 2.11: MFAT Scores for each Asset and overall MFAT score for Investigation 12 and 13.....	71
Table 3.1:: Details of Problem Formulation for Case Study	91
Table 3.2: Species composition in case study area	92
Table 3.3: Range of ACO parameters investigated for each algorithm.....	109
Table 3.4: Adopted ACO parameters for each algorithm.....	109
Table 3.5: Details of investigations for trade-offs between environmental allocation and total ecological response	114

Table 3.6: Details of number of species per asset and number of years considered in total ecological response objective ($g=1$) for Investigations 1-5 and 7-10	115
Table 3.7: Details of investigations conducted as part of examining the trade-offs between environmental flow, wetland ecological response and floodplain ecological response	115
Table 3.8: Details of number of species per asset and number of years considered in wetland ecological response ($g=1$) and floodplain ecological response ($g=2$) objectives for Investigation 6.....	117
Table 3.9: Details of investigations conducted as part of the assessment of the impact of additional regulators	118
Table 3.10: MFAT Score and allocation at the breakpoint for each investigation, as well as the rate at which the MFAT score increases per 1,000GL environmental allocation before and after the breakpoints.....	122
Table 3.11: Maximum MFAT Scores and corresponding allocations (GL/5yr) for each Investigation	122
Table 3.12: Maximum MFAT scores for each Allocation and Investigation	128
Table 3.13: Maximum MFAT Scores and associated allocations achieved for each regulator in operation	131
Table 3.14: MFAT scores achieved for each Allocation and Investigation for the 1,200 GL/month system constraint.....	132
Table 3.15: MFAT scores achieved for each Allocation and Investigation for the 1,800 GL/month system constraint.....	132
Table 4.1: Details of Problem Formulation for Case Study	153
Table 4.2: Species Composition in Case Study Area.....	154
Table 4.3: Details of the Number of Species per Asset in the Total Ecological Response Objective ($g=1$) for all Investigations.....	157
Table 4.4: Details of Candidate Inputs and Selected Inputs for all five ANNs	161
Table 4.5: Statistical Properties of the Data (Number of Observations = 106)	161

Table 4.6: Parameter Values Ranges Tested and Final Selected Parameters for each ANN.....	162
Table 4.7: Error Measures for all Forecasting ANN Models.....	164
Table 4.8: Range of PACOA Parameters Investigated and Values Selected	171
Table 4.9: Details of Methods Used	172