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-ACO3) ...................................................... 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

3.4.2 Impact of additional regulators

3.5 Results and Discussion

3.5.1 Impact of upstream flow constraints

3.5.1.1 Impact on Optimal Trade-off Curve

3.5.1.2 Impact on Effectiveness of Various Environmental Flow Allocations

3.5.2 Impact of Additional Regulators

3.5.2.1 Impact on Optimal Trade-off Curve

3.5.2.2 Impact on Effectiveness of Various Environmental Flow Allocations

3.5.3 Limitations

3.6 Summary and Conclusion

4 An adaptive ant colony optimization framework for scheduling environmental flow management alternatives under varied environmental water availability conditions (Paper 3)

4.1 Introduction

4.2 Proposed Adaptive Optimization Approach for the Optimal Scheduling of Environmental Flow Management Alternatives

4.3 Methodology

4.3.1 Case Study

4.3.2 Problem Formulation

4.3.2.1 Specification of Ecological Assets and Indicators

4.3.2.2 Identification of Planning Horizon, Time and Update Intervals

4.3.2.3 Selection of Management Alternatives and Suboptions

4.3.3 Specification of Objective Function and Constraints
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
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 EFMAs 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 EFMAs 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 gigaliters (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 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 1st Year (1983-1984), 10th Year (1992-1993) and 20th 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