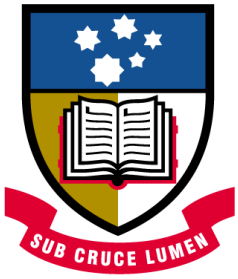

Multiobjective Genetic Algorithm Optimization of Water Distribution Systems Accounting for Economic Cost, Greenhouse Gas Emissions and Reliability

Wenyan Wu

BSc, MES, MEng

Thesis submitted in fulfillment of the requirements for the degree of Doctor of Philosophy

The University of Adelaide

Faculty of Engineering, Computer and Mathematical Sciences

School of Civil, Environmental and Mining Engineering

To my family - my mum, dad,
beloved husband and son.

Abstract

Multiobjective optimization is becoming an increasingly important approach for both the design and operation of water distribution systems (WDSs). Given the multiobjective nature of these problems, multiobjective optimization is expected to provide decision makers with increased insight into the tradeoffs between competing objectives and alternative solutions of WDSs, which might benefit the water industry, society and environment. Due to the advances in computing technology and the development of fast multiobjective sorting algorithms, research activities into the application of multiobjective algorithms to WDS design and operation have increased significantly in the past decade. Minimization of economic cost and maximization of network reliability are the two most commonly considered objectives in WDS optimization. In addition, some environment related issues, such as energy conservation, have been incorporated into the optimization of WDSs. However, the leading environmental concern – Greenhouse gas (GHG) emissions – has not yet been addressed directly in the field of WDS optimization. Consequently, this research incorporates GHG emission minimization as an objective directly into the optimal design of WDSs, together with the economic objective of minimizing cost and the hydraulic reliability objective of maximizing surplus power factor via a multiobjective approach.

The major research contributions are presented in six journal publications. These publications describe the motivation and methodology to incorporate GHG emission minimization as an objective of WDS optimization; explore the tradeoffs between the traditional objective of minimizing life cycle cost and the environmental objective of minimizing life cycle GHG emissions; investigate the sensitivity of these tradeoffs to a number of factors, including

the discount rate, electricity tariffs and emission factors used in the objective function evaluation process, the price of carbon under a potential emissions trading scheme and the use of fixed-speed or variable-speed pumps; and finally examine the impact of the inclusion of the hydraulic reliability objective of maximizing surplus power factor on WDS optimization account for economic cost and GHG emissions.

In addition, two technical issues have also been solved in order to achieve the overall research aim. First, an optimization based generic pump power estimation method has been developed in this research to efficiently estimate the size and pump power of the pumps required for different network configurations, thus variable-speed pumps can be incorporated into the optimal design of WDSs. Secondly, a new hydraulic reliability measure based on the concept of surplus power factor has been incorporated into the optimal design of WDSs. The advantage of this hydraulic measure over currently used hydraulic reliability measures is that it can be used for WDSs involving the delivery of water into storage facilities, where other measures have failed.

The overall contribution of this research is the incorporation of GHG emission consideration into the design optimization of WDSs together with the traditional economic and reliability objectives via a multiobjective approach. It is anticipated that this research will lead to a new paradigm for the optimization of WDSs in the real world.

Statement of Originality

I, *Wenyan Wu*, hereby declare that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution to Wenyan Wu 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.

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 being made available on the web, via the University's digital research repository, the Library catalogue, the Australian Digital Thesis Program (ADTP) and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

Signed: ……Date: ……..

Acknowledgments

Above all, I would like to thank my supervisors, Professor Angus Simpson and Professor Holger Maier, for their invaluable guidance, support and encouragement throughout the course of my PhD research. Without their enthusiasm and dedication, this thesis would not be possible.

I would like to thank all the staff of the School of Civil, Environmental and Mining Engineering for their support and help over the years of my PhD study. I am most grateful to Dr. Stephen Carr for his computing support. I would also like to show my gratitude to Professor Graeme Dandy who allowed me to spend time to complete my thesis while working for him as a Research Associate. In addition, I would like to acknowledge eResearch SA for the super-computing facilities provided for this research.

Many thanks go to my fellow postgraduate students within the School for sharing their research experience with me. I would never forget the help with program development I received from Dr. Robert May and Dr. Michael Leonard in the early stages of my PhD. I am also fortunate to have Dr. Aaron Zecchin as my "neighbor" in the office. The enjoyable discussions with Dr. Aaron Zecchin are an unforgettable part of my PhD study.

Thanks also go to Mr. Peter Horne for accomplishing the tedious task of proofreading the draft of this thesis.

Finally, I would like to thank my parents, Mr. Jianguo Wu and Ms. Li Cui, for providing me the opportunity to study in Australia and supporting me emotionally and financially during my PhD research. I am truly indebted to my husband, Tung, for his support, patience, encouragement and most

importantly for sharing the joy and frustration over the course of my research. Last but not least, I also owe a lot to my son, Tian, who brought me joy and hope during a very difficult time of my life.

Table of Contents

Journal Publications

1. Wu, W., Simpson, A. R., and Maier, H. R. (2010). "Accounting for Greenhouse Gas Emissions in Multiobjective Genetic Algorithm Optimization of Water Distribution Systems." *Journal of Water Resources Planning and Management*, 136(2), 146-155.

2. Wu, W., Maier, H. R., and Simpson, A. R. (2010). "Single-Objective versus Multi-Objective Optimization of Water Distribution Systems Accounting for Greenhouse Gas Emissions by Carbon Pricing." *Journal of Water Resources Planning and Management*, 136(5), 555-565.

3. Wu, W., Simpson, A. R., and Maier, H. R. (2012) "Incorporation of Variable-speed Pumping in Multiobjective Genetic Algorithm Optimization of the Design of Water Transmission Systems." *Journal of Water Resources Planning and Management*, (in press).

4. Wu, W., Simpson, A. R. and Maier, H. R. (2012). "Sensitivity of Optimal Tradeoffs between Cost and Greenhouse Gas Emissions for Water Distribution Systems to Electricity Tariff and Generation." *Journal of Water Resources Planning and Management.* 138(2), 182-186.

5. Wu, W., Maier, H. R. and Simpson, A. R. (2011) "Surplus Power Factor as a Resilience Measure for Assessing Hydraulic Reliability in Water Transmission System Optimization." *Journal of Water Resources Planning and Management*. 137(6), 542-546.

6. Wu, W., Maier, H. R. and Simpson, A. R. (2012). "Multiobjective Optimization of Water Distribution System Design Accounting for Economic Cost, Greenhouse Gas Emissions and Hydraulic Reliability." *Water Resources Research.* (submitted).

List of Figures

List of Tables

List of Abbreviations

ABARE	Australian Bureau of Agricultural and Resource Economics
ACOA	Ant Colony Optimization Algorithms
CE	Cross-Entropy
CO_2-e	Carbon dioxide equivalent
DICL	Ductile iron cement mortar lined
EA	Evolutionary algorithm
FCV	Flow control valve
FORM	First Order Reliability Method
FSP	Fixed speed pump
GA	Genetic algorithm
GHG	Greenhouse gas
HMT	Her Majesty's Treasury
IPCC	Intergovernmental Panel on Climate Change
MOGA	Multi-objective Genetic Algorithm [an algorithm developed by Fonseca and Fleming (1993)]
NSGA	Non-dominated Sorting Genetic Algorithm
NYT	New York tunnel
PVA	Present value analysis
SA	Simulated Annealing
SFLA	Shuffled Frog Leaping Algorithms
SPEA	Strength Pareto Evolution Algorithm
VEGA	Vector Evaluated Genetic Algorithm
VFD	Variable frequency drive
VSP	Variable speed pump
WBGA	Weight-based Genetic Algorithm

WDS	Water distribution system
WSMGA	Water System Multiobjective Genetic Algorithm
WTS	Water transmission system