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Decision Support System for Planning of Integrated Water Reuse Projects

Submitted by

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

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Abstract

The availability of fresh water supplies throughout the world has been getting scarcer over the past several decades, leading to existing or impending water shortages in many regions. In this context, water reuse has emerged as a genuine and reliable alternative that can be used to supplement, and in some cases substitute traditional water sources.

The practice of water reclamation and reuse has developed tremendously in the last century. With the rate of growth projected to increase even further, water reuse schemes of larger size will have to be planned, addressing an ever expanding list of technological, environmental, social and financial considerations. Therefore, decision support systems (DSS) are acutely needed to assist the planners of future water reuse schemes.

The DSS developed in this thesis and embodied in the WTRNet (Water Treatment for Reuse with Network Distribution) software tool takes into account the interactions that exist between the individual schemes components (treatment trains, distribution system and end-users of reclaimed water) in evaluation and selection of most promising design alternatives. Comprising of a simulation and optimisation components, the DSS provides a user-friendly platform for evaluation and optimisation of integrated water reuse schemes.

The numbers of potential design alternatives for schemes of different size are determined, and are shown to be substantially reduced by using rules that determine feasible treatment trains. Optimisation algorithms appropriate for schemes of different size are developed and tested on case studies to verify the DSS, which includes a novel and efficient linear programming methodology of least-cost sizing of reclaimed water distribution systems.

The benefits of evaluation in the proposed manner are demonstrated by deriving optimal water reuse schemes for the City of Waterloo, Ontario, Canada. The results of application of WTRNet on the case study indicate that the selection of optimal treatment alternatives based on different criteria has potentially significant effect on the cost of optimal alternatives, and that the selection of end-users requires a structured approach that takes into account factors other than their demand and location relative to the source.

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Table of Contents

List of Figures

List of Tables

List of Publications

Joksimovic, D. and D.A. Savic. (2006). Cost Management and Optimisation. Chapter 3 in "Water Reuse System Management Manual – AQUAREC", Edited by D. Bixio and T. Wintgens, Office for Official Publications of the European Communities, Luxembourg.

Joksimovic, D., D.A. Savic and G.A. Walters. (2006). An Integrated Approach to Least-Cost Planning of Water Reuse Schemes. Water Science & Technology: Water Supply, 6(5), pp 93-100.

Joksimovic, D., D.A. Savic, G.A. Walters, D. Bixio, K. Katsoufidou, S.G. Yiantsios, B. Janosova, P. Hlavinek. (2006) Development and Validation of System Design Principles for Water Reuse Systems, Proceedings of Integrated Concepts for Reuse of Upgraded Wastewater, Barcelona, Spain.

Joksimovic, D., J. Kubik, P. Hlavinek, D.A. Savic, G.A. Walters. (2006). Development of an Integrated Simulation Model for Treatment and Distribution of Reclaimed Water. Desalination, 188, pp. 9-20.

Bixio, D., C. Thoeye, J. De Koning, **D. Joksimovic**, D. Savic, T. Wintgens, T. Melin. (2006). Wastewater Reuse in Europe. Desalination, 187, pp. 89-101.

Joksimovic, D., J. Kubik, P. Hlavinek, D. Savic, G. Walters (2005) Development of an Integrated Simulation Model for Treatment and Distribution of Reclaimed Water, Integrated Concepts in Water Recycling, Proceedings of ICWR 2005 Conference, Khan, S.J., Muston, M.H. and Schäfer, A.I. (Eds.), Wollongong, Australia, pp. 343-354.

Joksimovic, D., J. Kubik, P. Hlavinek, D. Savic, G. Walters. (2005). Simulation Model for Integrated Planning of Water Reuse Schemes. Proceedings of 20th Annual WateReuse Symposium, Denver, USA.

Bixio, D., B. De heyder, H. Cikurel, M. Muston, V. Miska, **D. Joksimovic**, A.I. Schäfer, A. Ravazzini, A. Aharoni, D. Savic and C. Thoeye. (2005). Municipal wastewater reclamation: where do we stand? An overview of treatment technology and management practice. Water Science and Technology: Water Supply, 5(1), pp 77-85.

Joksimovic, D., J. Kubik, P. Hlavinek, D. Savic, G. Walters. (2004). Development of a Simulation Model for Water Reuse Systems. Proceedings of IWA 4th World Water Congress and Exhibition, Marrakech, Morocco.

Bixio, D., B. De heyder, H. Cikurel, M. Muston, V. Miska, **D. Joksimovic**, A.I. Schäfer, A. Ravazzini, A. Aharoni, D. Savic and C. Thoeye (2004). Municipal Wastewater reclamation: where do we stand? An overview of treatment technology and management practice. Proceedings of IWA 4th World Water Congress and Exhibition, Marrakech, Morocco.

List of Symbols and Abbreviations

AHP	Analytical Hierarchy Process
ASPP	Assembly Sequence Planning Problem
ASR	Aquifer Storage and Recovery
BOD_5	Biochemical Oxygen Demand (5-day)
CAPDET	Computer Assisted Procedure for the Design and Evaluation of Wastewater Treatment Systems
CBR	Case Based Reasoning
CRF	Capital Recovery Factor
DAF	Dissolved Air Floatation
DP	Dynamic programming
DSS	Decision support system
EA	Evolutionary algorithm
EM	Electro-mechanical (equipment)
EMO	Evolutionary Many-objective Optimisation
GA	Genetic algorithm
GIS	Geographical Information System
ILP	Integer Linear Programming
LP	Linear programming
LTWS	Long Term Water Strategy
MCA	Multicriteria Decision Analysis
MCDM	Multicriteria Decision Making
MENA	Middle East and North Africa
MILP	Mixed integer linear programming
MINLP	Mixed integer non-linear programming
MPM	Multiplicative Penalty Method
NFP	Network Flow Programming
NLP	Network Linear Programming

NPV	Net Present Value
NSGA-II	Fast Elitist Non-Dominated Sorting Genetic Algorithm
O&M	Operation and maintenance
PE	Serviced area population equivalents
RoW	Region of Waterloo
SAT	Soil Aquifer Treatment
STW	Sewage Treatment Works
UP	Unit Process
USEPA	United States Environmental Protection Agency
WHO	World Health Organisation
WTRNet	Water Treatment for Reuse and Network Distribution
WWTP	Wastewater treatment plant