RESEARCH CAPABILITY – HOLGER R MAIER

(http://www.adelaide.edu.au/directory/holger.maier)

1. Big Data and Machine Learning

Water authorities spend significant amounts of money on instrumentation, data collection and data storage. However, while these data contain significant amounts of information about system behaviour and performance, this information is often not used to and support operational and planning decisions. Big data and machine learning approaches can be used to capitalise on already significant investments in data collection by extracting as much information from existing data as possible to support decisions for very little additional cost. Our research group has made significant contributions in relation to the development and application of machine learning approaches for the extracting information from existing data sets, the development of predictive and forecasting models from existing data and the development of surrogate / meta models for improving the computational efficiency of simulation models for the purposes of optimisation / sensitivity and uncertainty analysis.

1.1 Improved extraction of information / relationships from existing datasets

Extracting as much information from existing data sets as possible is vitally important. This includes the relative strength of the relationships between variables, as well as potential redundancy in information. In addition, methods for achieving this need to cater to non-linear relationships between variables. Our group has developed improved methods for extracting information / relationships from existing datasets that addresses all of the above criteria. Sample publications dealing with these issues include:

Reis S., Seto E., Northcross A., Quinn N.W.T., Convertino M., Jones R.L., Maier H.R., Schlink U., Steinle S., Vieno M. and Wimberly M.C. (2015) **Integrating modelling and smart sensors for environmental and human health**, *Environmental Modelling and Software*, **74**, 238-246, DOI:10.1016/j.envsoft.2015.06.003.

Li X., Zecchin A.C. and Maier H.R. (2015) **Improving Partial Mutual Information-based input variable selection by consideration of boundary issues associated with bandwidth estimation**, *Environmental Modelling and Software*, **71**, 78-96, DOI: 10.1016/j.envsoft.2015.05.013 [**PMI SOFTWARE**].

Li X., Maier H.R. and Zecchin A.C. (2015) **Improved PMI-based input variable selection approach for artificial neural network and other data driven environmental and water resource models**, *Environmental Modelling and Software*, **65**, 15-29, DOI:10.1016/j.envsoft.2014.11.028

Galelli S., Humphrey G.B., Maier H.R., Castelletti A., Dandy G.C. and Gibbs M.S. (2014) **An evaluation framework for input variable selection algorithms for environmental data-driven models**, *Environmental Modelling and Software*, **62**, 33-51, DOI:

10.1016/j.envsoft.2014.08.015. [**IVS4EM FRAMEWORK WEBSITE** INCLUDING BENCHMARK DATA AND SOFTWARE]

Fernando T.M.K.G., Maier H.R. and Dandy G.C. (2009) **Selection of input variables for data driven models: An average shifted histogram partial mutual information estimator approach**, *Journal of Hydrology*, **367(3-4)**, 165-176, DOI: 10.1016/j.jhydrol.2008.10.019.

May R.J., Maier H.R., Dandy G.C. and Fernando T.M.K.G. (2008) **Non-linear variable selection for artificial neural networks using partial mutual information**. *Environmental Modelling and Software*, **23(10-11)**, 1312-1326, DOI:10.1016/j.envsoft.2008.03.007. [DOWNLOAD: PMI INPUT SELECTION SOFTWARE: AS EXCEL ADD-IN, AS C++ LIBRARY]

Bowden G.J., Dandy G.C. and Maier H.R. (2005) **Input determination for neural network models in water resources applications: Part 1 - Background and methodology**. *Journal of Hydrology*, **301(1-4)**, 75-92, DOI: 10.1016/j.jhydrol.2004.06.021.

1.2 Development of robust approaches to developing data-driven predictive models

Data-driven models, such as artificial neural networks, have the potential to be powerful tools for prediction and forecasting using existing data. However, as these methods are relatively new, robust methods and guidelines for their development are lacking. However, such guidelines are particularly pertinent to these types of models, as they are extremely flexible and therefore open to bad model development practice and therefore the development of unreliable and misleading models. In order to address this issue, our research group has developed improved methods and guidelines for the various stages of the development of data-driven models, and artificial neural networks in particular.

- Overall approach

Mount N.J., Maier H.R., Toth E., Elshorbagy A., Solomatine D., Chang F.-J. and Abrahart R.J. **Data-driven modelling approaches for social-hydrology: Opportunities and challenges within the Panta Rhei Science Plan**, *Hydrological Sciences Journal*, **61(7)**, 1192-1208, DOI: 10.1080/02626667.2016.1159683.

Wu W., Dandy G.C. and Maier H.R. (2014) **Protocol for developing ANN models and its application to the assessment of the quality of the ANN model development process in drinking water quality modeling**, *Environmental Modelling and Software*, **54**, 108-127, DOI: 10.1016/j.envsoft.2013.12.016.

Maier, H.R., Jain A., Dandy, G.C. and Sudheer, K.P. (2010) **Methods used for the development of neural networks for the prediction of water resource variables in river systems: Current status and future directions**, *Environmental Modelling & Software*, **25(8)**, 891-909, DOI: 10.1016/j.envsoft.2010.02.003.

Maier H.R. and Dandy G.C. (2001) **Neural network based modelling of environmental variables: a systematic approach**. *Mathematical and Computer Modelling*, **33(6-7)**, 669-682, DOI: 10.1016/S0895-7177(00)00271-5. [DOWNLOAD: PAPER]

- Data Processing

Bowden G.J., Dandy G.C. and Maier H.R. (2003) **Data transformation for neural network models in water resources applications**. *Journal of Hydroinformatics,* **5(4)**, 245-258 [Download: Paper]

- Input determination (see also Section 1.1)

May R.J., Dandy G.C., Maier H.R. and Nixon J.B. (2008) **Application of partial mutual information variable selection to ANN forecasting of water quality in water distribution systems**, *Environmental Modelling and Software*, **23(10-11)**, 1289-1299, DOI:10.1016/j.envsoft.2008.03.008. [DOWNLOAD: PMI INPUT SELECTION SOFTWARE: AS EXCEL ADD-IN, AS C++ LIBRARY]

Bowden G.J., Maier H.R. and Dandy G.C. (2005) **Input determination for neural network models in water resources applications: Part 2 - Case study: Forecasting salinity in a river**. *Journal of Hydrology*, **301(1-4)**, 93-107, DOI: 10.1016/j.jhydrol.2004.06.020.

- Data splitting

Wu W., May R.J., Maier H.R. and Dandy G.G. (2013) **A benchmarking approach for comparing data splitting methods for modeling water resources parameters using artificial neural networks**, *Water Resources Research*, **49(11)**, 7598-7614, DOI: 10.1002/2012WR012713. [DOWNLOAD: DATA SPLITTING SOFTWARE: AS EXCEL ADD-IN, AS C++ LIBRARY]

May R.J., Maier H.R. and Dandy G.C. (2010) **Data splitting for artificial neural networks using SOM-based stratified sampling**, *Neural Networks*, **23(2)**, 283-294, DOI: 10.1016/j.neunet.2009.11.009. [DOWNLOAD: DATA SPLITTING SOFTWARE: AS EXCEL ADD-IN, AS C++ LIBRARY]

Bowden G.J., Maier H.R. and Dandy G.C. (2002) **Optimal division of data for neural network models in water resources applications**. *Water Resources Research*, **38(2)**, 2.1-2.11, DOI: 10.1029/2001WR000266

- Identification of model structure

Kingston G.B., Maier H.R. and Lambert M.F. (2008) **Bayesian model selection applied to artificial neural networks used for water resources modeling**, *Water Resources Research*, **44(4)**, W04419, DOI:10.1029/2007WR006155.

Maier H.R. and Dandy G.C. (1998) **The effect of internal parameters and geometry on the performance of back-propagation neural networks: an empirical study**.

Environmental Modelling and Software, **13(2)**, 193-209, DOI: 10.1016/S1364-8152(98)00020-6.

- Model calibration (training)

Li X., Zecchin A.C. and Maier H.R. (2014) **Selection of smoothing parameter estimators for General Regression Neural Networks - applications to hydrological and water resources modelling**, *Environmental Modelling and Software*, **59**, 162-186, DOI: 10.1016/j.envsoft.2014.05.010. [**SOFTWARE DOWNLOAD**]

Kingston G.B., Lambert M.F and Maier H.R. (2005) **Bayesian training of artificial neural networks used for water resources modeling**. *Water Resources Research*, **41(12)**, W12409, DOI:10.1029/2005WR004152.

Kingston G.B., Maier H.R. and Lambert M.F. (2005) **Calibration and validation of neural networks to ensure physically plausible hydrological modeling**. *Journal of Hydrology*, **314(1-4)**, 158-176, DOI: 10.1016/j.jhydrol.2005.03.013.

Maier H.R. and Dandy G.C. (1999) **Empirical comparison of various methods for training feedforward neural networks for salinity forecasting**. *Water Resources Research*, **35(8)**, 2591-2596, DOI: 10.1029/1999WR900150.

Maier H.R. and Dandy G.C. (1998) **Understanding the behaviour and optimising the performance of back-propagation neural networks: an empirical study**. *Environmental Modelling and Software*, **13(2)**, 179-191, DOI: 10.1016/S1364-8152(98)00019-X.

- Model validation

Humphrey G.B., Maier H.R., Wu W., Mount N.J., Dandy G.C., Abrahart R.J. and Dawson C.W. (2017) **Improved validation framework and R-package for artificial neural network models**, Environmental Modelling and Software, **92**, 82-106, DOI: 10.1016/j.envsoft.2017.01.023.

Kingston G.B., Maier H.R. and Lambert M.F. (2006) **A probabilistic method to assist knowledge extraction from artificial neural networks used for hydrological prediction**. *Mathematical and Computer Modelling,* **44(5-6)**, 499-512. [DOWNLOAD: PAPER]

Kingston G.B., Maier H.R. and Lambert M.F. (2005) **Calibration and validation of neural networks to ensure physically plausible hydrological modeling**. *Journal of Hydrology*, **314(1-4)**, 158-176, DOI: 10.1016/j.jhydrol.2005.03.013.

- Real-time deployment of model

Bowden G.J., Maier H.R. and Dandy G.C. (2012) **Real-time deployment of artificial neural network forecasting models - understanding the range of applicability**, *Water Resources Research*, **48(10)**, DOI:10.1029/2012WR011984.

1.3 *Application of data-driven prediction/forecasting models to a range of water/environmental engineering applications*

Our research group had applied data-driven models, and artificial neural networks in particular, to a number of problems in water, environmental and geotechnical engineering.

- Water quality in distribution systems

  Wu W., Dandy G.C. and Maier H.R. (2015) **Optimal control of total chlorine and free ammonia levels in a water transmission pipeline using artificial neural networks and genetic algorithms**, *Journal of Water Resources Planning and Management,* **141(7)**, 04014085, DOI: 10.1061/(ASCE)WR.1943-5452.0000486.

  May R.J., Dandy G.C., Maier H.R. and Nixon J.B. (2008) **Application of partial mutual information variable selection to ANN forecasting of water quality in water distribution systems**, *Environmental Modelling and Software*, **23(10-11)**, 1289-1299, DOI:10.1016/j.envsoft.2008.03.008. [DOWNLOAD: PMI INPUT SELECTION SOFTWARE: AS EXCEL ADD-IN, AS C++ LIBRARY]

  Bowden G.J, Nixon J.B., Dandy G.C., Maier H.R. and Holmes M. (2006) **Forecasting chlorine residuals in a water distribution system using a general regression neural network**. *Mathematical and Computer Modelling,* **44(5-6)**, 469-484, DOI: 10.1016/j.mcm.2006.01.006. [DOWNLOAD: PAPER]

  Gibbs M.S., Morgan N., Maier H.R., Dandy G.C., Nixon J.B. and Holmes M. (2006) **Investigation into the relationship between chlorine decay and water distribution parameters using data driven methods**. *Mathematical and Computer Modelling,* **44(5-6)**, 485-498, DOI: 10.1016/j.mcm.2006.01.007. [DOWNLOAD: PAPER]

- Water quality in source waters

  Maier H.R., Sayed T. and Lence B.J. (2001) **Forecasting cyanobacterium *Anabaena* spp. using B-spline neurofuzzy models**. *Ecological Modelling*, **146(1-3)**, 85-96, DOI: 10.1016/S0304-3800(01)00298-8.

  Maier H.R., Dandy G.C. and Burch M.D. (1998) **Use of artificial neural networks for modelling the incidence of cyanobacteria *Anabaena* spp. in River Murray, South Australia**. *Ecological Modelling*, **105(2/3)**, 257-272, DOI: 10.1016/S0304-3800(97)00161-0.

  Maier H.R. and Dandy G.C. (1996) **The use of artificial neural networks for the prediction of water quality parameters**. *Water Resources Research*, **32(4)**, 1013-1022, DOI: 10.1029/96WR03529.

- Water availability in source waters

  Humphrey G.B., Gibbs M.S., Dandy G.C. and Maier H.R. (2016) **A hybrid approach to monthly streamflow forecasting: integrating hydrological model outputs into a**

Bayesian artificial neural network, *Journal of Hydrology*, **540**, 623-640, DOI: 10.1016/j.jhydrol.2016.06.026.

Szemis J.M., Maier H.R. and Dandy G.C. (2014) **An adaptive ant colony optimization framework for scheduling environmental flow management alternatives under varied environmental water availability conditions**, *Water Resources Research*, **50(10)**, 7606-7625, DOI: 10.1002/2013WR015187

- Reliability and vulnerability of water supply and distribution systems

Broad D.B., Dandy G.C. and Maier H.R. (2015) **A systematic approach to determining metamodel scope for risk-based optimization and its application to water distribution system design**, *Environmental Modelling and Software*, **69**, 382-395, DOI:10.1016/j.envsoft.2014.11.015. [**EPANETINPUT FILE FOR PACIFIC CITY CASE STUDY**]

Beh E.H.Y, Maier H.R., Dandy G.C. and Kapelan Z. (2014) **Robust staged development of water supply systems**, *Procedia Engineering*, **89**, 864-869, DOI:10.1016/j.proeng.2014.11.518 [OPEN ACCESS].

- Pressures in water distribution systems

Broad D.R., Maier H.R. and Dandy G.C. (2010) **Optimal operations of complex water distribution systems using metamodels**, *Journal of Water Resources Planning and Management*, **136(4)**, 433-443, DOI: 10.1061/(ASCE)WR.1943-5452.0000052.

Broad D.R., Dandy G.C and Maier H.R. (2005) **Water distribution system optimisation using metamodels**. *Journal of Water Resources Planning and Management*, ASCE, **131(3)**, 172-180, DOI: 10.1061/(ASCE)0733-9496(2005)131:3(172)

- Optimal water treatment levels

Maier H.R., Morgan N. and Chow C.W.K. (2004) **Use of artificial neural networks for predicting optimal alum doses and treated water quality parameters**. *Environmental Modelling and Software*, **19(5)**, 485-494, DOI: 10.1016/S1364-8152(03)00163-4

- Water demand

This research was done as part of a final year research project and did not result in a journal paper

- Ecological health of rivers

Gee E.M., Mann E.H.G., Bowden G.J., Costelloe J., Puckridge J., Reid J.R.W. and Maier H.R. (2002) **Modelling fish responses to flow variability in Cooper Creek, South Australia: preliminary results from studies over two time periods**. *Riversymposium 2002*, Brisbane, Australia, 3-6 September.

- Rainfall runoff modelling

  Wu W., May R.J., Maier H.R. and Dandy G.G. (2013) **A benchmarking approach for comparing data splitting methods for modeling water resources parameters using artificial neural networks**, *Water Resources Research*, **49(11)**, 7598-7614, DOI: 10.1002/2012WR012713. [DOWNLOAD: DATA SPLITTING SOFTWARE: AS EXCEL ADD-IN, AS C++ LIBRARY]

  Kingston G.B., Maier H.R. and Lambert M.F. (2005) **Calibration and validation of neural networks to ensure physically plausible hydrological modeling**. *Journal of Hydrology*, **314(1-4)**, 158-176, DOI: 10.1016/j.jhydrol.2005.03.013

- Settlement of soils

  Shahin M.A., Jaksa M.B. and Maier H.R. (2005) **Neural network based stochastic design charts for settlement prediction**. *Canadian Geotechnical Journal*, **42(1)**, 110-120, DOI: 10.1139/t04-096.

  Shahin M.A., Maier H.R. and Jaksa M.B. (2003) **Settlement prediction of shallow foundations on granular soils using B-spline neurofuzzy models**, *Computers and Geotechnics,* **30(8)**, 637-647, DOI: 10.1016/j.compgeo.2003.09.004.

  Shahin M.A., Maier H.R. and Jaksa M.B. (2002) **Predicting settlement of shallow foundations using neural networks**. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE,* **128(9)**, 785-793, DOI: 10.1061/(ASCE)1090-0241(2002)128:9(785)

1.4 Increasing the computational efficiency of simulation models using meta/surrogate models

Simulation models of complex water systems can take tens of seconds or even minutes to run, especially when conducting extended period simulations or considering water quality. While this is not a problem for single model runs, this can be an issue when such models are run many thousands of times as part of optimisation and/or sensitivity and uncertainty analysis. In order to overcome this limitation, our research group has developed approaches for using artificial neural networks as computationally efficient surrogates or emulators (metamodels) of computationally expensive simulation model.

Broad D.B., Dandy G.C. and Maier H.R. (2015) **A systematic approach to determining metamodel scope for risk-based optimization and its application to water distribution system design**, *Environmental Modelling and Software*, **69**, 382-395, DOI:10.1016/j.envsoft.2014.11.015. [**EPANETINPUT FILE FOR PACIFIC CITY CASE STUDY**]

Broad D.R., Maier H.R. and Dandy G.C. (2010) **Optimal operations of complex water distribution systems using metamodels**, *Journal of Water Resources Planning and Management*, **136(4)**, 433-443, DOI: 10.1061/(ASCE)WR.1943-5452.0000052.

Broad D.R., Dandy G.C and Maier H.R. (2005) **Water distribution system optimisation using metamodels**. *Journal of Water Resources Planning and Management*, ASCE, **131(3)**, 172-180, DOI: 10.1061/(ASCE)0733-9496(2005)131:3(172)

2. Optimal Long-Term Water Resources and Infrastructure Planning Under Deep Uncertainty (Including Climate Change)

The planning of water infrastructure in the face of deep uncertainty, such as the impact of climate change, is complicated by a number of factors, such as the consideration of alternative, non-traditional sources of water, the need to consider multiple, often competing objectives (e.g. energy usage and greenhouse gas emissions, potential impacts on public health, reliability, robustness) and the need to consider long time frames. Uncertainties in future conditions also make it difficult to know at what point costly infrastructure investments should be made – premature investment could result in potential "white elephants", while delayed investment could result in water supply shortages. In order to address these issues, our research group has developed a number of approaches to determining the optimal mix of different water sources for regional water supply, to determine the optimal staging of water supply expansion and determination of the optimal capacity of existing systems.

2.1 Underlying concepts

Maier H.R., Guillaume J.H.A., van Delden H., Riddell G.A., Haasnoot M. and Kwakkel J.H. (2016) **An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together?**, *Environmental Modelling and Software*, **81**, 154-164, DOI: 10.1016/j.envsoft.2016.03.014

2.2 Determination of optimal mix of different water sources under deep uncertainty

Wu W., Dandy G.C., Maier H.R., Maheepala S., Marchi A. and Mirza F. (2017) **Identification of optimal water supply portfolios for a major city** (external link), *Journal of Water Resources Planning and Management*, **143(9)**: 05017007, DOI: 10.1061/(ASCE)WR.1943-5452.0000811.

Paton F.L., Maier H.R. and Dandy G.C. (2014) **Including adaptation and mitigation responses to climate change in a multi-objective evolutionary algorithm framework for urban water supply systems incorporating GHG emissions**, *Water Resources Research*, **50(8)**, 6285-6304, DOI:10.1002/2013WR015195.

Paton F.L., Dandy G.C. and Maier H.R. (2014) **Integrated framework for assessing urban water supply security of systems with non-traditional sources under climate change**, *Environmental Modelling and Software*, **60**, 302-319, DOI: 10.1016/j.envsoft.2014.06.018.

Paton F.L., Maier H.R. and Dandy G.C. (2013) **Relative magnitudes of sources of uncertainty in assessing climate change impacts on water supply security for the southern Adelaide water supply system**, *Water Resources Research*, **49(3)**, 1643-1667, doi:10.1002/wrcr.20153.

Maier H.R., Paton F.L., Dandy G.C. and Connor J.D. (2013) **Impact of drought on Adelaide's water supply system: Past, present, and future**. In K. Schwabe, J. Albiac, J.D. Connor, R.M Hassan and L.M. Gonzalea (Eds.) Drought in Arid and Semi-Arid Regions: A Multi-Disciplinary and Cross-Country Perspective, Springer, 41-62.

2.3 Determination of optimal sequencing / staging of infrastructure projects under deep uncertainty

Beh E.H.Y., Zheng F., Dandy G.C., Maier H.R. and Kapelan Z. (2017) **Robust optimization of water infrastructure planning under deep uncertainty using metamodels**, *Environmental Modelling and Software*, 93, 92-105, DOI: 10.1016/j.envsoft.2017.03.013.

Beh E.H.Y, Maier H.R. and Dandy G.C. (2015) **Adaptive, multi-objective optimal sequencing approach for urban water supply augmentation under deep uncertainty**, *Water Resources Research*, **51(3)**, 1529-1551, DOI:10.1002/2014WR016254.

Beh E.H.Y, Maier H.R. and Dandy G.C. (2015) **Scenario driven optimal sequencing under deep uncertainty**, *Environmental Modelling and Software*, **68**, 181-195, DOI:10.1016/j.envsoft.2015.02.006.

Beh, E.H.Y., Dandy G.C., Maier H.R. and Paton F.L. (2014) **Optimal sequencing of water supply options at the regional scale incorporating alternative water supply sources and multiple objectives**, *Environmental Modelling and Software*, **53**, 137-153, DOI: 10.1016/j.envsoft.2013.11.004.

2.4 Optimal design of infrastructure for localised water supply systems under deep uncertainty

Di Matteo M., Dandy G.C. and Maier H.R. (2017) **A multi-stakeholder portfolio optimization framework applied to stormwater best management practice (BMP) selection (external link)**, *Environmental Modelling and Software*, **97**, 16-31, DOI:10.1016/j.envsoft.2017.07.012.

Di Matteo M., Dandy G.C. and Maier H.R. (2017) **Multi-objective optimization of distributed stormwater harvesting systems**, *Journal of Water Resources Planning and Management*, **143(6)**, DOI: 10.1061/(ASCE)WR.1943-5452.0000756, 04017010.

Marchi A., Dandy G.C. and Maier H.R. (2016) **Integrated approach to the optimal design of aquifer storage and recovery stormwater harvesting schemes taking into account externalities and climate change**, *Journal of Water Resources Planning and Management*, **142(4)**, DOI: 10.1061/(ASCE)WR.1943-5452.0000628, 04016002.

Newman J., Dandy G.C. and Maier H.R. (2014) **Multiobjective optimization of cluster-scale urban water systems investigating alternative water sources and level of**

decentralization, *Water Resources Research*, **50(10)**, 7915-7938, DOI:10.1002/2013WR015233.

2.5 Development of bottom-up (scenario neutral) approaches to climate impact assessment

Culley S., Noble S., Yates A., Timbs M., Westra S., Maier H.R., Giuliani M. and Castelletti, A. (2016) **A bottom-up approach to identifying the maximum operational adaptive capacity of water resource systems to a changing climate**, *Water Resources Research*, DOI: 10.1002/2015WR018253.

Guo D, Westra S. and Maier H.R. (2016) **An R package for modelling actual, potential and reference evapotranspiration**, *Environmental Modelling and Software*, **78**, 216-224, DOI:10.1016/j.envsoft.2015.12.019

Guo D., Westra S. and Maier H.R. (2017) **An inverse approach to perturb historical rainfall data for scenario-neutral climate impact studies**, *Journal of Hydrology*, DOI:10.1016/j.jhydrol.2016.03.025

Guo D., Westra S. and Maier H.R. (2017) **Impact of evapotranspiration process representation on runoff projections from conceptual rainfall-runoff models**, *Water Resources Research*, **53(1)**, 435-454, DOI: 10.1002/2016WR019627.

Guo D., Westra S. and Maier H.R. (2017) **Sensitivity of potential evapotranspiration to changes in climate variables for different Australian climatic zones**, *Hydrology and Earth System Sciences*, **21(4)**, 2107-2126, DOI:10.5194/hess-21-2107-2017

Guo D., Westra S. and Maier H.R. **Use of a scenario-neutral approach to identify the key hydro-meteorological attributes that impact runoff from a natural catchment**, *Journal of Hydrology*, accepted 12/9/17

3. Optimal Design and Operation of Water Distribution Systems Considering the Water-Energy Nexus

The advent of climate change has had a number of impacts on the planning, design and operation of water distribution systems, including the need to pay closer attention to the water-energy nexus. This manifests itself in a number of ways, such as the need to consider trade-offs between costs and GHG decisions and the impact of renewable energy sources on how to best design and operate water distribution systems. Our research group has been at the forefront of developing novel approaches for dealing with these challenges.

Stokes C.S., Maier H.R. and Simpson A.R. (2016) **Effect of storage tank size on the minimization of water distribution system cost and greenhouse gas emissions while considering time-dependent emissions factors**, *Journal of Water Resources Planning and Management*, 142(2), 04015052-1 to 04015052-11, DOI: 10.1061/(ASCE)WR.1943-5452.0000582, 04015052.

Stokes C.S., Maier H.R. and Simpson A.R. (2015) **Water distribution system pumping operational greenhouse gas emissions minimization by considering time-dependent emissions factors**, *Journal of Water Resources Planning and Management*, **141(7)**, 04014088, DOI: 10.1061/(ASCE)WR.1943-5452.0000484.

Stokes C.S., Simpson A.R. and Maier H.R. (2015) **A computational software tool for the minimization of costs and greenhouse gas emissions associated with water distribution systems**, *Environmental Modelling and Software*, **69**, 452-467, DOI: 10.1016/j.envsoft.2014.11.004. [**WCEN FRAMEWORK SOFTWARE**]

Stokes C.S., Simpson A.R. and Maier H.R. (2014) **The Cost - Greenhouse Gas Emission Nexus for Water Distribution Systems including the Consideration of Energy Generating Infrastructure: An Integrated Optimization Framework and Review of Literature,** *Earth Perspectives 2014,* **1:9**, DOI:10.1186/2194-6434-1-9. DOWNLOAD: Paper, Supplementary Material].

Wu W., Maier H.R. and Simpson A.R. (2013) **Multiobjective optimization of water distribution systems accounting for economic cost, hydraulic reliability and greenhouse gas emissions**, *Water Resources Research*, **49(3)**, 1211-1225, doi:10.1002/wrcr.20120.

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, DOI: 10.1061/(ASCE)WR.1943-5452.0000169.

Wu W., Maier H.R. and Simpson A.R. (2010) **Single-objective versus multi-objective optimisation of water distribution systems accounting for greenhouse gas emissions by carbon pricing**, *Journal of Water Resources Planning and Management*, **136(5)**, 555-565, DOI: 10.1061/(ASCE)WR.1943-5452.0000072.

Wu W., Simpson A.R. and Maier H.R. (2010) **Accounting for greenhouse gas emissions in multi-objective genetic algorithm optimization of water distribution systems**, *Journal of Water Resources Planning and Management*, **136(2)**, 146-155, DOI: 10.1061/(ASCE)WR.1943-5452.0000020.

4. Development of Improved Approaches to the Optimisation of Real-World Problems

While formal optimisation approaches have the potential to assist with the identification of significantly better solutions, they are often treated as black boxes and fail to take account of the knowledge and experience of people who have been working in their respective fields and on their respective systems for many years. This not only excludes a significant amount of useful information from the optimisation process, but also inhibits the uptake of and trust in optimisation methods. In order to address this, our research group had developed hybrid approaches that combine the strengths of system / domain knowledge and experience and formal optimisation methods. In addition, methods have been developed that enable the behaviour of optimisation algorithms to be understood better, increasing their computational efficiency, thereby making them to be applied more easily in practice.

4.1 *Incorporation of domain knowledge / end user experience / system understanding into formal optimisation approaches*

Nguyen D.C.H., Dandy G.C., Maier H.R. and Ascough II J.C. (2016) **Improved ant colony optimization for optimal crop and irrigation water allocation by incorporating domain knowledge**, *Journal of Water Resources Planning and Management*, **142(9)**, DOI: 10.1061/(ASCE)WR.1943-5452.0000662, 04016025.

Bi W., Dandy G.C. and Maier H.R. (2016) **Use of domain knowledge to increase the convergence rate of evolutionary algorithms for optimizing the cost and resilience of water distribution systems**, *Journal of Water Resources Planning and Management*, **142(9)**, DOI: 10.1061/(ASCE)WR.1943-5452.0000649, 04016027.

Wu W., Maier H.R., Dandy G.C., Leonard R., Bellette K., Cuddy S. and Maheepala S. (2016) **Including stakeholder input in formulating and solving real-world optimisation problems: generic framework and case study**, *Environmental Modelling and Software*, 79, 197-213, DOI:10.1016/j.envsoft.2016.02.012.

Bi W., Dandy G.C. and Maier H.R. (2015) **Improved genetic algorithm optimization of water distribution system design by incorporating domain knowledge**, *Environmental Modelling and Software*, **69**, 370-381, DOI: 10.1016/j.envsoft.2014.09.010.

4.2 *Increasing of computational efficiency of optimisation process*

- Incorporation of increased understanding of optimisation process

Bi W., Maier H.R. and Dandy G.C. (2016) **Impact of starting position and searching mechanism on evolutionary algorithm convergence rate**, *Journal of Water Resources Planning and Management*, **142(9)**, DOI: 10.1061/(ASCE)WR.1943-5452.0000655, 04016026.

Zheng F., Zecchin A.C., Maier H.R. and Simpson A.R. (2016) **Comparison of the searching behavior of NSGA-II, SAMODE and Borg MOEAs applied to water distribution system design problems**, *Journal of Water Resources Planning and Management*, **142(7)**, DOI: 10.1061/(ASCE)WR.1943-5452.0000650, 04016017.

Zecchin A.C., Simpson A.R., Maier H.R., Marchi A. and Nixon J.B. (2012) **Improved understanding of the searching behaviour of ant colony optimization algorithms applied to the water distribution design problem**, *Water Resources Research*, **48(9)**, DOI:10.1029/2011WR011652.

- Determination of improved methods for determining optimisation model parameters

Zheng F., Zecchin A.C., Newman J.P., Maier H.R. and Dandy G.C. **An adaptive convergence-trajectory controlled ant colony optimization algorithm with application to water distribution system design problems**, *IEEE Transactions on Evolutionary Computation,* DOI: 10.1109/TEVC.2017.2682899

Gibbs M.S., Maier H.R. and Dandy G.C. (2015) **Using characteristics of the optimisation problem to determine genetic algorithm population size when evaluation number is limited**, *Environmental Modelling and Software*, **69**, 226-239, DOI: 10.1016/j.envsoft.2014.08.023.

Gibbs M.S., Maier H.R. and Dandy G.C. (2011) **Relationship between problem characteristics and the optimal number of genetic algorithm generations**, *Engineering Optimization*, **43(4)**, 349-376, DOI: 10.1080/0305215X.2010.491547.

Gibbs M.S., Dandy G.C. and Maier H.R. (2010) **Calibration and optimization of the pumping and disinfection of a real water supply system**, *Journal of Water Resources Planning and Management*, **136(4)**, 493-501, DOI: 10.1061/(ASCE)WR.1943-5452.0000060.

Gibbs M.S., Maier H.R. and Dandy G.C. (2010) **Comparison of genetic algorithm parameter setting methods for chlorine injection optimization**, *Journal of Water Resources Planning and Management*, **136(2)**, 288-291, DOI: 10.1061/(ASCE)WR.1943-5452.0000033.

Gibbs M.S., Dandy G.C. and Maier H.R. (2008) **A genetic algorithm calibration method based on convergence due to genetic drift**. *Information Sciences*, **178(14)**, 2857-2869, DOI:10.1016/j.ins.2008.03.012.

Zecchin A.C., Simpson A.R., Maier H.R. and Nixon J.B. (2005) **Parametric study for an ant algorithm applied to water distribution system optimisation**. *IEEE Transactions on Evolutionary Computation*, **9(2)**, 175-191, DOI: 10.1109/TEVC.2005.844168.

- Surrogate / meta modelling (see Section 1.4)

5. Development of Improved Decision Support Approaches under Uncertainty

5.1 *Development of improved approaches to determining the sensitivity of decisions to uncertainties*

Often, models are used to determine which options are better than others. However, the models used to assess the options are subject to a number of uncertainties. In order to account for this, our research group has developed novel approaches for determining how sensitive decisions (and not model outputs) are to these uncertainties.

Ganji A., Maier H.R. and Dandy G.C. (2016) **A modified Sobol' sensitivity analysis method for decision-making in environmental problems**, *Environmental Modelling and Software*, **75**, 15-27, DOI:10.1016/j.envsoft.2015.10.001.

Ravalico J.K., Dandy G.C. and Maier H.R. (2010) **Management option rank equivalence (MORE) - A new method of sensitivity analysis for decision-making**, *Environmental Modelling & Software*, **25(2)**, 171-181, DOI:10.1016/j.envsoft.2009.06.012. [***Environmental Modelling and Software Best Paper Award 2010: Generic Modelling and/or Software Methods***]

Ravalico J.K., Maier H.R and Dandy G.C (2009) **Sensitivity analysis for decision-making using the MORE method - A Pareto approach**, *Reliability Engineering & System Safety*, **94(7)**, 1133-1244, DOI: 10.1016/j.ress.2009.01.009.

5.2 *Development of improved approaches to ranking options using multi-criteria decision-analysis under uncertainty*

Multi-criteria decision analysis is used to rank discrete options based on a number of criteria, as well as stakeholder preferences. However, it is important to understand the robustness of these rankings in the face of uncertainties of data/information and stakeholder preferences. In order to account for this, our research group has developed a number of novel approaches for achieving this.

Hyde K.M. and Maier H.R. (2006) **Distance-based and stochastic uncertainty analysis for multi-criteria decision analysis in Excel using visual basic for applications**. *Environmental Modelling and Software,* **21(12)**, 1695-1710, DOI: 10.1016/j.envsoft.2005.08.004.

Hyde K.M., Maier H.R. and Colby C.B. (2005) **A distance-based uncertainty analysis approach to multi-criteria decision analysis for water resource decision making**,

Journal of Environmental Management, **77(4)**, 278-290, DOI: 10.1016/j.jenvman.2005.06.011.

Hyde K.M., Maier H.R and Colby C. (2003) **Incorporating uncertainty in the PROMETHEE MCDA Method**. *Journal of Multi-Criteria Decision Analysis*, **12(4-5)**, 245-259 (published in 2005), DOI: 10.1002/mcda.361.

Hyde K.M., Maier H.R. and Colby C. (2004) **Reliability-based approach to multi-criteria decision analysis for water resources**. *Journal of Water Resources Planning and Management*, ASCE, **130(6)**, 429-438, DOI: 10.1061/(ASCE)0733-9496(2004)130:6(429).

5.3 *Decision support system for assessment of policy and planning investment options for optimal natural hazard mitigation*

Prof Maier is currently the research leader of the Economics and Strategic Decisions research cluster of the Bushfire and Natural Hazards Cooperative Research C entre (http://www.bnhcrc.com.au/research/cluster/economics-strategic-decisions), as well as the leader of a project focussed on the development of a decision support system for the assessment of policy and planning investment options for optimal natural hazard mitigation (http://www.bnhcrc.com.au/research/economics-policy-and-decision-making/230), which has developed a prototype DSS for the greater Adelaide region and is in the process of developing similar DSSs for greater and peri-urban Melbourne, all of Tasmania and Perth.

Newman J.P., Maier H.R., Riddell G.A., Zecchin A.C., Daniell J., Schaefer A., van Delden H., Khazai B., O'Flaherty M.J. and Newland C.P. (2017) **Review of literature on decision support systems for natural hazard risk reduction: Current status and future research directions (external link)**, *Environmental Modelling and Software*, **96**, 378-409, DOI:10.1016/j.envsoft.2017.06.042.

Golding P., Kapadia S., Naylor S., Schulz J., Maier H.R., Lall U. and van der Velde, M. (2017) **Framework for minimising the impact of regional shocks on global food security using multi-objective ant colony optimisation (external link)**, *Environmental Modelling and Software*, **95**, 303-319, DOI:10.1016/j.envsoft.2017.06.004.

6. Optimal Water Allocation for Environmental, Agricultural and Water Supply Purposes

There are often competing demands on available water resources from a variety of users, such as agriculture, cities and the environment. Our research team has developed a range of approaches to optimising ecological, agricultural and water supply security outcomes in constrained water environments.

Nguyen D.C.H., Ascough II J.C., Maier H.R., Dandy G.C. and Andales A.A. **Optimization of irrigation scheduling using Ant Colony algorithms and an advanced cropping system model (external link)**, *Environmental Modelling and Software*, **97**, 32-45, DOI:10.1016/j.envsoft.2017.07.002.

Nguyen D.C.H., Maier H.R., Dandy G.C. and Ascough II, J.C. (2016) **Framework for computationally efficient optimal crop and water allocation using ant colony optimization**, *Environmental Modelling and Software*, **76**, 37-53, DOI:10.1016/j.envsoft.2015.11.003.

Szemis J.M., Maier H.R. and Dandy G.C. (2014) **An adaptive ant colony optimization framework for scheduling environmental flow management alternatives under varied environmental water availability conditions**, *Water Resources Research*, **50(10)**, 7606-7625, DOI: 10.1002/2013WR015187.

Gibbs M.S., Dandy G.C. and Maier H.R. (2014) **Assessment of the ability to meet environmental water requirements in the Upper South East of South Australia**, *Stochastic Environmental Research and Risk Assessment*, **28(1)**, 39-56, DOI:10.1007/s00477-013-0735-9.

Szemis J.M., Dandy G.G. and Maier H.R. (2013) **A multi-objective ant colony optimization approach for scheduling environmental flow management alternatives with applications to the River Murray**, Australia, *Water Resources Research*, **49(10)**, 6393-6411, DOI: 10.1002/wrcr.20518.

Szemis J.M., Maier H.R. and Dandy G.C. (2012) **A framework for using ant colony optimization to schedule environmental flow management alternatives for rivers, wetlands and floodplains**, *Water Resources Research*, **48(8)**, DOI:10.1029/2011WR011276.

Rowan T.S.C., Maier H.R., Connor J. and Dandy G.C. (2011) **An integrated dynamic modeling framework for investigating the impact of climate change and variability on irrigated agriculture**, *Water Resources Research*, **47(7)**, W07520, DOI:10.1029/2010WR010195.

7. Development of Improved Approaches to Hydrological Modelling

Simplified conceptual models are most commonly used in hydrological modelling. However, we generally have no means of assessing how well these models represent complex processes under different circumstances. Our research group has developed a virtual laboratory approach for assessing the accuracy and improving the performance of simplified hydrological models.

Argent R.M., Sojda R.S., Guipponi C., McIntosh B., Voinov A.A. and Maier H.R. (2016) **Best practices for conceptual modelling in environmental planning and management**, *Environmental Modelling and Software*, **80**, 113-121, DOI: 10.1016/j.envsoft.2016.02.023

Li L., Lambert M.F., Maier H.R., Partington D. and Simmons C.T. (2015) **Assessment of the internal dynamics of the Australian Water Balance Model under different calibration regimes**, *Environmental Modelling and Software*, **66**, 57-68, DOI:10.1016/j.envsoft.2014.12.015.

Li L., Maier H.R., Partington D., Lambert M.F and Simmons C.T. (2014) **Performance assessment and improvement of recursive digital baseflow filters for catchments with different physical characteristics and hydrological inputs**, *Environmental Modelling and Software*, **54**, 39-52, DOI: 10.1016/j.envsoft.2013.12.011

Partington D., Brunner P., Frei S., Simmons C.T., Werner A.D., Therrien R., Maier H.R., Dandy G.C. and Fleckenstein J. (2013) **Interpreting streamflow generation mechanisms from integrated surface-subsurface flow models of a riparian wetland and catchment**, *Water Resources Research*, **49(9)**, 5501-5519, DOI: 10.1002/wrcr.20405.

Li L., Maier H.R., Lambert M.F, Simmons C.T and Partington D. (2013) **Framework for assessing and improving the performance of recursive digital filters for baseflow estimation with application to the Lyne and Hollick filter**, *Environmental Modelling and Software*, **41**, 163-175, DOI: 10.1016/j.envsoft.2012.11.009

Partington D., Brunner P., Simmons C.T., Werner A.D, Therrien R., Maier H.R. and Dandy G.C. (2012) **Evaluation of outputs from automated baseflow separation methods against simulated baseflow from a physically based, surface water - groundwater flow model**, *Journal of Hydrology*, **458-459** (2012), 28-39, DOI: 10.1016/j.jhydrol.2012.06.029.

Gibbs M.S., Maier H.R. and Dandy G.C. (2012) **A generic framework for regression regionalization in ungauged catchments**, *Environmental Modelling and Software*, **27-28**, 1-12, DOI:10.1016/j.envsoft.2011.10.006.

Partington D., Brunner P., Simmons C.T., Therrien R., Werner A.D, Dandy G.C. and Maier H.R. (2011) **A hydraulic mixing-cell method to quantify the groundwater component**

of streamflow within spatially distributed fully integrated surface water - groundwater flow models, *Environmental Modelling and Software*, **26(7)**, 886-898, DOI:10.1016/j.envsoft.2011.02.007.