THE Water Research FOUNDATION

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Comprehensive Analysis of Alternative Water Supply Projects Compared to Direct Potable Reuse

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Prepared by:

Benjamin D. Stanford, Ph.D.
Hazen and Sawyer (Currently with American Water)

Stephanie K. L. Ishii, Ph.D.
Grace Johns, Ph.D.
Hazen and Sawyer

Michalis Hadjikakou, Ph.D.
University of New South Wales (Currently with Deakin University)

Stuart Khan, Ph.D.
Thomas O. Wiedmann, Ph.D.
University of New South Wales

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THE Water Research FOUNDATION

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For more information, contact:

The Water Research Foundation

Alexandria, VA Office
1199 North Fairfax Street, Suite 900
Alexandria, VA 22314-1445
Tel: 571.384.2100
www.werf.org
werf@werf.org

Denver, CO Office
6666 West Quincy Avenue
Denver, Colorado 80235-3098
Tel: 303.347.6100
www.waterrf.org
Info@WaterRF.org

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Hazen and Sawyer, University of New South Wales

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Research Team

Principal Investigators:
Benjamin D. Stanford, Ph.D.
Hazen and Sawyer (Currently with American Water)

Stuart J. Khan, Ph.D.
University of New South Wales

Tommy Wiedmann, Ph.D.
University of New South Wales

Grace Johns, Ph.D.
Hazen and Sawyer

Michalis Hadjikakou, Ph.D.
University of New South Wales

Project Team:
Hazel Rowley, Ph.D.
University of New South Wales

Yumi Kobayashi, Ph.D.
University of New South Wales

Stephanie Ishii, Ph.D.
Hazen and Sawyer

Jack Kiefer, Ph.D.
Hazen and Sawyer

Alan Karnovitz, Ph.D.
Hazen and Sawyer

Ian B. Law, Ph.D.
IBL Solutions

WRF Project Advisory Committee

Tom Chesnutt
A&N Technical Services, Inc.

Steve Piper
U.S. Bureau of Reclamation

Saied Delagah
U.S. Bureau of Reclamation

Water Research Foundation Staff

Justin Mattingly
Research Manager

Carrie Capuco, J.D.
Director of Communications

Abstract and Benefits

Abstract:

Many utilities and practitioners within the water community are finding an increasing number of potential benefits of potable reuse, including reduced energy requirements, construction costs, operational costs, and the ability to better control and maintain water quality within engineered buffer systems. Direct potable reuse (DPR) may provide an opportunity to allow potable reuse in situations where a suitable environmental buffer is not available for indirect potable reuse (IPR). However, there is a need for a more nuanced understanding of the relative costs and benefits of various DPR or IPR Water Supply Options (WSOs) and their different pumping, treatment and delivery requirements.

DPR remains one of many possible options that will need to be considered vis-à-vis other technologies and solutions, including a 'no action' scenario. It is critical that potential WSOs be compared in a transparent, publicly accessible manner to facilitate sound management-level decision making, public engagement, and education regarding the benefits and costs of alternative WSOs.

The purpose of this project was first and foremost to develop a quantitative framework with an accompanying electronic tool interface to allow any utility to conduct a triple bottom line (TBL) evaluation of direct potable reuse projects compared to other alternative water supply systems such as indirect potable reuse, groundwater or surface water development, desalination, and demand management, among others. This project was designed to support the Water Research Foundation's

The outcome of Reuse-14-03 is an ambitious attempt to develop a sophisticated and generalizable quantitative modelling framework capable of computing impacts across multiple TBL indicators for a wide range of user-specified treatment trains. The Water Supply Evaluation Tool (WaterSET) is a product of the team's efforts in developing and validating a TBL framework for water supply evaluation. The user interface portion of the model is packaged as a compact, user-friendly Excel© spreadsheet tool enabling water utilities to carry out their own TBL assessments and select the best WSO configurations for their own purposes. The computational engine and all underlying functions have been coded in Matlab© to ensure high performance and full automation, though a Matlab license is not required for the user to access and run WaterSET. All model inputs, cost curves, cost indices and environmental intensity data may be updated at any stage to ensure the longevity of the tool.

This report presents the conceptual and theoretical framework underpinning WaterSET. The modelling framework incorporates economic and environmental input-output analyses, lifecycle cost analysis, and social impact analysis into a triple bottom line multi-criteria decision analysis (MDCA) of WSOs. This report provides a thorough description of the framework and model development, provides examples of the tool's application through case studies, and includes a user manual that provides step-by-step guidance on the implementation of WaterSET with definitions of all the input variables and outputs used for comparing alternative scenarios. Easy instructions on how to install and operate the tool are also provided and includes all necessary links required to download the software.

Benefits:

- The TBL framework developed for this study provides a means for utilities to evaluate WSOs and treatment approaches for a single water supply or across a suite of WSOs. A key feature of the approach used here is that the MCDA has been decoupled from the outputs of the TBL model, which allows users to view the quantitative impacts of water supply options separately from the MCDA output.
- Provides an opportunity for utilities to determine if, and by how much, different weighting factors may impact the ranking of a specific WSO or treatment approach. Both the MCDA output and the TBL output have value in communicating risks and impact with stakeholders and therefore WaterSET should provide a means by which these can be developed and presented in a clear, transparent manner to stakeholders.

The benefits of WaterSET are described as follows:

- Provides a flexible approach to TBL analysis because all underlying data can be easily expanded and updated **–** e.g., cost indices (ENR CCI and BLS), cost curves (engineering textbooks and locally specific data), environmental extensions through CEDA (Suh 2009) and Eora (Lenzen et al. 2013), eGrid through the EPA (EPA 2015). These aforementioned datasets are updated regularly.

- Enables a relatively quick means for scoping and examining how various water supply options compare at the unit process level.

- Facilitates sensitivity analyses of water supply rankings as a function of various treatment, conveyance, and criteria weightings to ultimately determine hot spots of burden and areas with the greatest opportunity for improvement.

Keywords: Economics, water supply options, one water, integrated resource planning, triple bottom line (TBL), potable reuse, environmental, social, impacts assessment.

Contents

Tables

Figures

Acronyms and Abbreviations

CAPEX	Capital expenditures
DPR	Direct potable reuse
EE-MRIO	Environmentally extended multi-regional input output model
IOT	Input-Output Table
IPR	Indirect potable reuse
LCA	Lifecycle analysis
LCC	Lifecycle cost
MDCA	Multi-criteria decision analysis
MRIOT	Multi-Regional Input-Output Table
NAIC	North American Industrial Classification
OPEX	Operation and maintenance expenditures
PAC	Project advisory committee
TBL	Triple bottom line
WSO	Water supply option

Executive Summary

The purpose of this project was first and foremost to develop a quantitative framework with an accompanying electronic tool interface to allow any utility to conduct a triple bottom line (TBL) evaluation of direct potable reuse projects compared to other alternative water supply systems such as indirect potable reuse, groundwater or surface water development, desalination, and demand management, among others. The outcome of Reuse-14-03 is a quantitative modelling framework, packaged as the Water Supply Evaluation Tool (WaterSET), capable of computing impacts across multiple TBL indicators for a wide range of user-specified water supply options at the unit process level.

The user interface portion of the model is packaged as a compact, user-friendly Excel spreadsheet tool enabling water utilities to carry out their own TBL assessments and select the best water supply option configurations for their own purposes. The computational engine and all underlying functions have been coded in Matlab© to ensure high performance and full automation, though a Matlab license is not required or user to access and run WaterSET. All model inputs, cost curves, cost indices and environmental intensity data may be updated at any stage to ensure the longevity of the tool. The WaterSET framework and tool, including requested user information, background datasets and algorithms, produced outputs, and decision making criteria, were influenced by an industry survey, stakeholder workshops, and utility interviews that were conducted as part of this study. Overall, WaterSET is a triple bottom line input-output based life cycle analysis that incorporates economic and environmental input-output analyses, lifecycle cost analysis, and social impact analysis into a single evaluation for the characterization and ranking of water supply options.

WaterSET begins with a list of user-defined water supply options to be evaluated. Input data provided by the user are used by the model to calculate estimates of capital, operations and maintenance costs. For each water supply option under consideration, users are asked to input information related to the geographical location, associated treatment processes, conveyance, fuel consumption, and other areas that make one water supply option unique from another. The tool then calculates values for the economic and environmental criteria using an input-output based hybrid – lifecycle analysis (IO-LCA) which relies upon a large environmentally extended multi-regional input-output (EE-MRIO) table of data. Onsite fuel consumption and pumping impacts are estimated using process-based LCA – these impacts relate mostly to energy and carbon emissions and are additional to those calculated by the EE-MRIO approach. The values for the social criteria are calculated separately using the social impact analysis model. The environmental, economic, and social criteria used to characterize and compare water supply options were decided upon based on utility input during the project workshops, the literature review, and the expertise of the project team in evaluating water supply options. Figure ES-1 shows an example of one output provided by WaterSET: a radar chart in which the unweighted triple bottom line results are shown for all water supply options across the model's quantitative criteria. Water supply options with a more favorable impact for a given criterion receive a higher score relative to the other water supply options.

If opted for by the user, all criteria values are then input into the multi-criteria decision analysis (MDCA) which involves the assignment of weights to each criterion and converting all criteria scores to a common measurement system that can be aggregated into a total score for each water supply option. Criteria with high user-defined weightings have a more significant influence on the final score than criteria with low user-defined weightings. The common measurement system used by WaterSET is a prioritization method known as Evaluation of Mixed Data (EVAMIX). The water supply options are ultimately ranked in terms of favorability using the final EVAMIX score, which accounts for quantitative criteria scores calculated by the model, qualitative criteria scores input by the user, and criteria weightings input by the user. Figure ES-2 shows an example of the second output provided by WaterSET: the weighted MCDA results, in which the qualitative and quantitative triple bottom line results are coupled with criteria weightings to determine one numerical score per water supply option.

The TBL framework developed for this study and described in this report provides a means for utilities to evaluate water supply options and treatment approaches for a single water supply or across a suite of WSOs. A key feature of the approach used here is that the MCDA has been decoupled from the outputs of the TBL model, which allows users to view the quantitative impacts of water supply options separately from the MCDA output. It also provides an opportunity for utilities to determine if, and by how much, different weighting factors may impact the favorability of a specific water supply option or treatment approach. Both the MCDA output and the TBL output have value in communicating risks and impact with stakeholders and therefore WaterSET should provide a means by which this can be developed and presented in a clear, transparent manner to stakeholders.

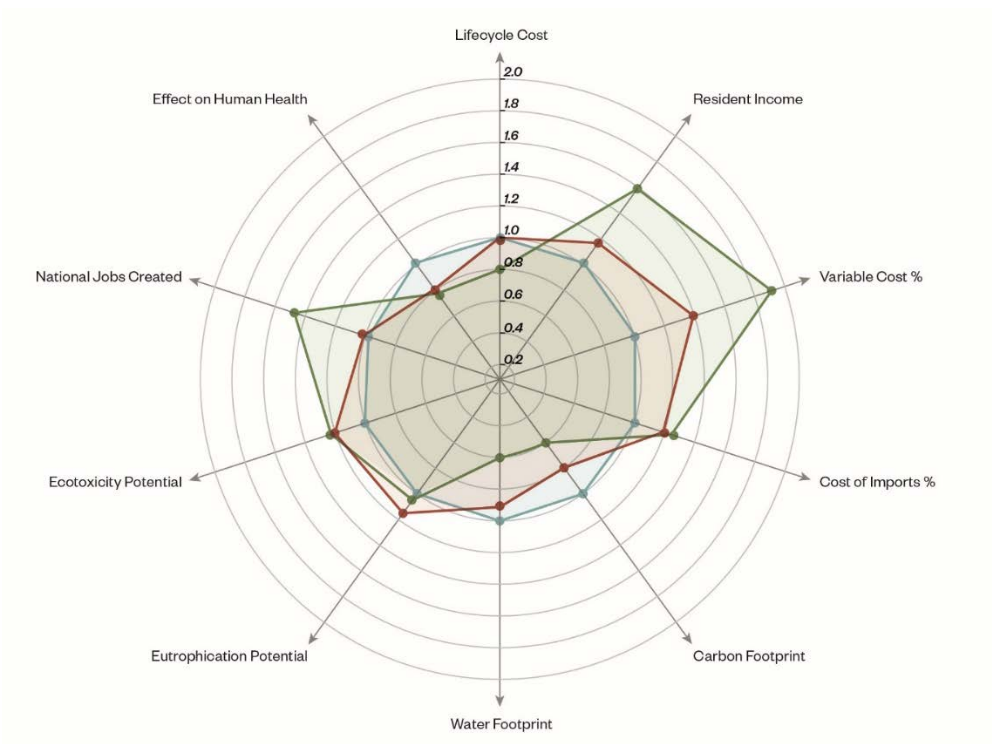

Figure ES-1. A Radar Chart Used to Visualize Unweighted Triple Bottom Line Results for Three Water Supply Options.

The baseline water supply receives a score of 1.0 for all quantitative criteria.
The water supply options with a more favorable impact for a given criterion receive a score greater than 1.0, while those with a less favorable impact receive a score of less than 1.0.

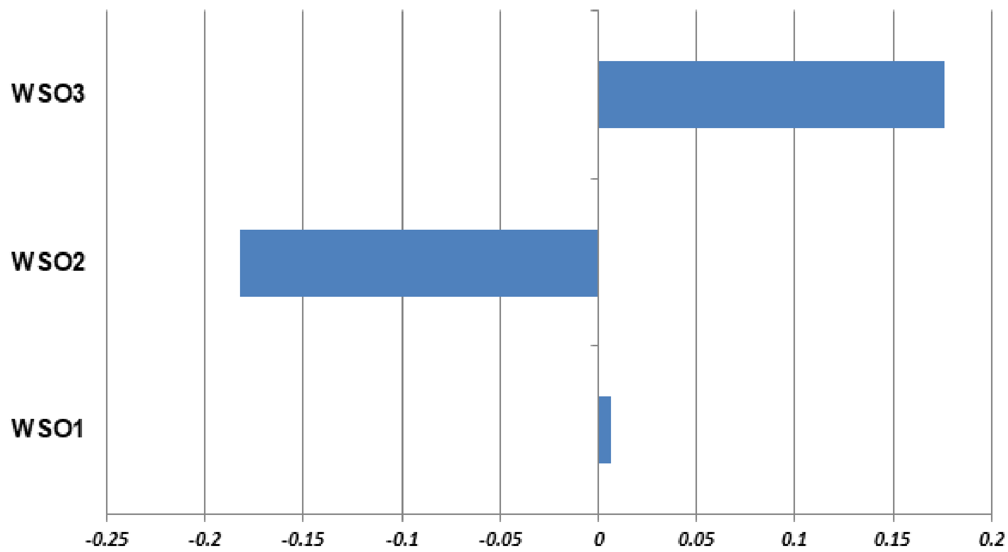

Figure ES-2. An Example of Multi-Criteria Decision Analysis Results in Which One Aggregated Score is Attributed to Each Water Supply Option Using the EVAMIX Algorithm.

Numerical scores are relative across water supply options within a given evaluation and do not have significance across WaterSET runs.

CHAPTER 1

Introduction

This section provides background information on triple bottom line decision making in the context of water supply planning, spanning traditional approaches and the novelties of the framework and tool presented herein.

1.1 Background

Population growth, urbanization, climate change, and the limited availability of water from traditional sources are creating water scarcity in many parts of the world (Leverenz et al. 2011; Tarroja et al. 2014; Larsen et al. 2016). In many water scarce areas, the imminent threat of water shortage has forced government officials and water utilities to consider alternatives to conventional water supplies to address uncertainty in future supply and demand by diversifying their water supply portfolio. Non-conventional water resources typically used to meet shortfalls or provide added supply are desalination of seawater and brackish water, importation of water from geographically distinct regions, and water reuse (treated wastewater) (FAO 2003). While supply augmentation is necessary and inevitable, the selection of water supply options (WSOs) should avoid imposing major cost and environmental impacts, while ensuring that societal and other values are respected (Cooley and Ajami 2012; Tarroja et al. 2014; Escriva-Bou et al. 2015).

While desalination is used to augment potable water supplies, treated wastewater is traditionally either restricted to non-potable uses such as irrigation or returned to an environmental buffer (a river, lake, or aquifer) before being reharvested and subsequently treated again for potable use, through a process known as indirect potable reuse (Rodriguez et al. 2009; Khan 2011). Indirect potable reuse (IPR) is already practiced in many areas of the country and the world, both as part of intentional IPR projects as well as part of *de facto* environmental processes whereby one community's effluent becomes the next community's drinking water supply.

In all IPR projects, be they intentional or unintentional, reclaimed water spends time in an environmental buffer such as a river, lake, reservoir, or aquifer prior to being recovered, further treated, and then distributed to drinking water customers. Environmental buffers in IPR projects have had many important functions attributed to them, including potential additional treatment of waterborne pathogens and chemical contaminants, the provision of 'time to respond' to potential water treatment incidents, and improvement of the public's perception of potable water reuse.

In contrast to IPR, the supply of highly treated reclaimed water directly to a drinking water treatment plant or distribution system is known internationally as direct potable reuse (DPR) (Khan 2011; Tchobanoglous et al. 2011; NWRI 2012). DPR differs from more established approaches to potable water reuse by the absence of an environmental buffer(Drewes and Khan 2014). The technology behind DPR is, for the most part, not new but with the exception of Windhoek (Namibia), where the Goreangab DPR plant has been operating more or less continuously since the late 1960s (Du Pisani 2006; Grant et al. 2012), there have been very few large-scale implementations. However, worldwide applications of diverse potential treatment trains are increasing (Gerrity et al. 2013).

Many utilities and practitioners within the water community are recently finding an increasing number of potential benefits of DPR relative to IPR, including reduced energy requirements, reduced construction costs, reduced operational costs, and the ability to better control and maintain water quality within engineered buffer systems (Schroeder et al. 2012; Trussell et al. 2012; Trussell et al. 2013)[1]. DPR may provide an opportunity to allow potable reuse in situations where a suitable environmental buffer is not available for IPR. However, potential obstacles or disadvantages for DPR, relative to IPR and other technologies, are primarily related to public perception and acceptance rather than science or engineering (Dolnicar et al. 2010; Dolnicar et al. 2011). Public acceptance of DPR and water reuse in general is essential for its successful implementation, as a lack of public acceptance may lead to loss of trust between the public and the water industry, political opposition, and eventual failure of the project. For example, the failure of two previously proposed IPR projects, one that was part of Southeast Queensland government's Western Corridor Project and the other being the City of San Diego's 1999 San Vicente Reservoir Augmentation Project, has been largely attributed to the lack of time, resources, and research dedicated to community outreach and a resulting lack of public acceptance for the projects(Chan 2014). Another important issue is the need for a more nuanced understanding of the relative costs and benefits of various DPR or IPR WSOs and their different pumping, treatment and delivery requirements.

DPR remains one of many possible options that will need to be considered vis-à-vis other technologies or solutions, including a 'no action' scenario (Raucher 2013). It is critical that potential WSOs be compared in a transparent, publicly accessible manner to facilitate sound management-level decision making, public engagement, and education regarding the benefits and costs of alternative WSOs. This calls for a comprehensive and objective evaluation methodology for comparing alternative WSOs, which fits in nicely within a triple bottom line (TBL) framework. This is aptly expressed in one of the key conclusions of a recent report by the Australian Academy of Technological Sciences and Engineering (ATSE) (ATSE 2013, p.5):

"Ultimately, water supply decision-making should be based on an objective assessment of available water supply options to identify the most economically, environmentally and socially sustainable solution".

1.2 Triple Bottom Line for Selecting Water Supply Options

Triple bottom line evaluations have been previously conducted in the context of water supply planning and otherwise, with various nuances being attributed to individual studies.

1.2.1 Existing Approaches – Merits and Limitations

A trend towards increasing drought and water scarcity in many parts of the U.S. and Australia creates the need to consider augmentation of existing water supplies. While there are often many possible alternative choices available, the challenge is to achieve supply augmentation in a way that adheres to sustainability principles (Marques et al. 2015). Despite the existence of several generalized sustainability frameworks intended to guide broad operations management for water and wastewater utilities (Hellström et al. 2000; Balkema et al. 2002; Lundin and Morrison 2002; Mitchell 2006; Lundie et al. 2008; Liner and deMonsabert 2011; ATSE 2012; Schimmoller et al. 2015; Ries et al. 2016), there is presently no specialized triple bottom line (TBL) model or holistic framework for considering among a range of WSOs at the level of individual unit processes.

[1] This is the case especially when compared to the more widely used alternative of desalination, where relatively high energy requirements and operating costs are of particular concern (Cooley and Ajami 2012; WRDC 2012).

The TBL assessment framework provides an established accounting approach for concurrently quantifying economic, environmental, and social implications for any business decision or project (Foran et al. 2005; Wiedmann et al. 2009; Thabrew et al. 2017). Water utilities are expected to operate on the basis that both short- and long-term financial sustainability and success should go hand-in-hand with social justice and environmental protection (Marques et al. 2015; GRI 2016). For water and wastewater utilities and other water-related authorities, TBL represents a widely accepted, transparent, and defensible means to compare the total (economic, environmental and social) benefits and costs of any investment vis-à-vis other alternatives, including the option of taking no action (Raucher 2013; Schimmoller et al. 2015; Venkatesh et al. 2015; Ries et al. 2016). A critical aspect of the TBL process is the selection and quantification of the various comparison criteria to be used in the assessment. As the number of decision making criteria increases, the breadth of considered impacts also tends to increase; however, the inclusion of an increasing number of criteria may also cause a decrease in the certainty associated with the scoring for each. Thus, it is important that variations in certainty and the corresponding impact that each criterion should have on the overall outcome are addressed via criteria weightings or other means.

Given the many possible options and configurations within a single WSO, such as, for instance, many possible DPR treatment trains (Gerrity et al. 2013; Hummer and Eden 2016; Mattingly 2017), it becomes important to be able to compare them and make decisions using information at the unit process level. Venkatesh et al. (2015) aptly demonstrate the benefits of TBL approaches for selecting among individual treatments processes, however their methodology is tailored entirely to their specific case study and does not provide a basis for a more holistic TBL assessment. Their analysis is also restricted to the water treatment stage (chemicals and energy), with no consideration of important aspects such as conveyance and piping, solids disposal, and other supply chain impacts.

Another commonly used framework for understanding the full economic value of goods is the Total Economic Value (TEV) framework (AWRCE 2013; 2014). The TEV framework allows the user to identify the value of consumptive water use and the values of environmental and social benefits that are aggregated into a TEV expressed in monetary units. This type of approach is also employed in recent work in the U.S. (Stratus Consulting 2011; Raucher 2013). As a general consensus, the outcomes from this type of evaluation are quantified and monetized to the extent feasible, whereas any important outcomes that could not be monetized or quantified in a reasonably credible manner are described in qualitative terms (Stratus Consulting 2011). Combining quantitative and qualitative indicators should therefore be seen as an accepted practice in the industry when attempting to integrate a comprehensive list of indicators that take into account economic, environmental and social impacts (Hajkowicz and Collins 2007). However, this is still limited by the need to standardize the measurement of benefits and costs such as through monetization to easily and objectively compare alternatives

In addition to the TEV and existing TBL approaches, other quantitative (Hellström et al. 2000; Balkema et al. 2002; Lundin and Morrison 2002; Stokes and Horvath 2006; Del Borghi et al. 2013; Marques et al. 2015) and qualitative (Dolnicar et al. 2010; Ries et al. 2016) sustainability assessment approaches have been developed. However, none of the aforementioned frameworks include the full supply chain of economic, environmental and social impacts associated with a variety of conventional and non-conventional processes nor do they allow the user to visualise and compare different unit processes based on a complete set of criteria and alternative weightings. The rising popularity of potable reuse technologies (Rodriguez et al. 2009; Khan 2011; Leverenz et al. 2011) and the growing range of possible alternative treatment trains (Gerrity et al. 2013) creates the need to develop a framework that can account for the considerable heterogeneity in likely TBL impacts arising from different WSOs as well as variants of the same WSO.

1.2.2 Towards a Holistic TBL Assessment Framework

The family of life cycle assessment (LCA) TBL approaches offer the most promising basis for developing a holistic sustainability framework for assessing current and future WSOs (Lundin and Morrison 2002; Stokes and Horvath 2006; Shahabi et al. 2014; Zhou et al. 2014). A recent ATSE report includes a hypothetical comparison of four WSOs (seawater desalination, IPR, DPR, and dual pipe reuse) with respect to four criteria: estimates of 1) power use, 2) material use, 3) greenhouse gas emissions, and 4) capital cost (ATSE 2013).

In this kind of TBL assessment, each criterion is quantified in its native value (i.e. not monetized). The end results are a series of charts where each of the WSOs are compared against each other based on their performance in each criterion. Although this approach provides accurate process-based results and may be easily replicated for any given water supply option, there is no consideration of qualitative (social) indicators and, as the authors acknowledge, does not offer a comprehensive quantification of 'upstream' and 'downstream' effects in the same way as a full-blown LCA (ATSE 2013).

An even more holistic sustainability framework which allows the use of various methodologies or tools within its context, is described in Lundie et al. (2006) and further elaborated in Lundie et al. (2008). The framework consists of six principal phases:

i. Defining the problem and objectives.

ii. Considering preliminary options.

iii. Determining sustainability criteria and weightings.

iv. Screening different options.

v. Performing detailed assessments.

vi. Recommending a preferred option.

This framework emphasizes iteration based on constant feedback from stakeholders. It also stresses the need for qualitative criteria such as public acceptance, health concerns, or aesthetic effects. Most importantly, the framework incorporates concurrent use of highly rigorous quantitative methodologies such as LCA or other TBL or 'foot printing' methods, as well as multi-criteria decision analysis (MCDA). This framework is an appropriate conceptual method which is fully consistent with the framework developed during this project, and the previously described TBL assessment methods.

1.2.3 The Importance of Including MCDA to Inform Decision Making

The premise of any sustainability assessment or TBL framework in the urban water services domain should be to provide the user with practical information that can inform decision-making. When multiple economic, environmental, and social criteria are combined, the importance assigned to each will largely dictate the outcome. It is therefore extremely important to consider this issue through a rigorous quantitative approach, one that not only produces a single aggregate result but also allows a sensitivity analysis to understand the impact of different opinions regarding the weighting (or importance) assigned to each of the evaluation criteria.

Multi-criteria decision analysis (MCDA), also known as multi-criteria assessment (MCA), provides "a general framework for supporting complex decision-making situations with multiple and often conflicting objectives" (Saarikoski et al. 2015, p 1). The fundamental aim of MCDA is to facilitate the overall evaluation of alternatives (e.g., WSOs), given those alternatives' individual evaluations using a potentially long list of criteria or indicators that capture any number of key dimensions of the decision-making problem. MCDA also provides a structured, explicit, and transparent way to account for the relative importance of the criteria to decision makers.

Water management is a complex, multi-objective problem where outcomes are measured in different ways and expressed in different units (Hajkowicz and Collins 2007). Given the large number of criteria required to comprehensively evaluate the performance of any given WSO, making an informed decision based on the raw TBL evaluations alone would be so cognitively challenging as to be virtually impossible. Therefore, MCDA can add significant value to the evaluation by facilitating a structured, data-driven, participatory, and robust decision process that takes into account the legitimate stakeholder preferences in a transparent and auditable way (Marques et al. 2015). Hajkowicz and Collins (2007) argue that MCDA has been proven to have a positive impact on the auditability, transparency, and analytic rigour of water management decisions.

While not a feature of all MCDA methods, many have no theoretical limit to the number or type of criteria they can handle (Cinelli et al. 2014). Some are also able to concurrently take both quantitative (cardinal) and semi-quantitative (ordinal) indicators into account in a meaningful way (de Montis et al. 2005; Rowley et al. 2012; Cinelli et al. 2014). Section 3.5.9 details the choice of MCDA method and how it was tailored to the purposes of the project.

1.3 Study Approach and Preliminary Steps for Model Development

The purpose of this project was first and foremost to develop a quantitative framework with an accompanying electronic tool interface to allow any utility to conduct a triple bottom line (TBL) evaluation of direct potable reuse projects compared to other alternative water supply systems such as indirect potable reuse, groundwater or surface water development, desalination, and demand management, among others. This project was designed to support the WateReuse Research Foundation's (now the Water Research Foundation, WRF) Direct Potable Reuse (DPR) initiative and to provide a means for utilities to evaluate various water supply options in their communities. The first task of this project was to conduct a **State of the Industry Assessment** that began with a review of existing evaluation frameworks, economic assessments, and tools available in the literature including those funded by WRF.

Interviews with project partner utilities identified elements from previous evaluation frameworks that have been of significant value, obtained recommendations on focus areas, and determined stakeholder perceptions and value systems to include in the TBL methodology. The partner utilities were: Coliban Water, VIC, Australia; Midcoast Water, NSW, Australia; Port Macquarie-Hastings Council, NSW, Australia; Tampa Bay Water, FL, USA; Orange County Water District, CA, USA; Hampton Roads Sanitation District, southeast VA, USA; Wannon Water, VIC, Australia; Water Research Australia, SA, Australia; and Water Services Association of Australia, NSW, Australia.

The first of two project workshops was held at the University of New South Wales, Sydney, on February 12, 2015. The workshop was attended by Project Team members, the Australian Water Recycling Centre of Excellence, Water Research Australia, the project's case study partners (Port Macquarie-Hastings Council and Coliban Water), other water utility partners (Sydney Water, City West Water and MidCoast Water), and academics from the University of Technology, Sydney. The results of the workshop included identification of 1) Useful and redundant elements of existing sustainability frameworks; 2) Water supply options (WSOs); and 3) a Comprehensive list of potential TBL criteria. The complete list of workshop participants and short summarised outcomes, including subsequent modifications to the framework on the basis of comments and feedback received, are provided in Appendix A.

Other partner utilities were consulted via interviews to further develop a list of WSOs that would be included in developing the methodology and software. In particular, four utilities (Tampa Bay Water, Orange County Water District, Coliban Water, and Port Macquarie-Hastings) provided the types of WSOs that have been previously identified and/or evaluated, as well as those that may be considered in the future, to help ensure that a sufficient breadth of options was addressed by the tool. These WSOs noted by each utility are provided in Table 1-1**.**

Table 1-1. Water Supply Options Under Consideration for Four Utility Partners.

Potential Supply Options:	**DPR**	**IPR**	**Purple Pipe**	**GW**	**Desalination**	**Imported Water**	**New Dams/ Lakes**	**Inter-Connection**
Coliban Water	💧	💧	💧	💧		💧	💧	💧
Port Macquarie-Hastings	💧	💧	💧	💧	💧	💧	💧	
Tampa Bay Water	💧	💧	💧	💧	💧	💧		💧
Orange County Water District	💧	💧	💧	💧	💧	💧		

The full list of WSOs identified in the workshop that were considered during the development of the TBL methodology and computer tool, along with a summary of the advantages, considerations and concerns of each WSO are provided in Table 1-2.

Table 1-2. List of Water Supply Options to Include in the TBL Methodology and Computerized Tool.

Water Supply Option	**Advantages**	**Considerations/Concerns**
DPR/IPR	Expands use of existing supply (retains available resources locally), potentially reduced energy for pumping	Need for new technology / membranes / treatment process; public opinion; trade-offs between types of IPR/DPR processes, consider costs to obtain regulatory approval
Desalination	Uses seawater/brackish water, no freshwater depletion	Brine disposal, energy-intensive, expensive for irrigation, not suitable for most inland areas.
New dam (reservoir)	Proven & popular, flood mitigation, recreation possibilities, hydropower generation	Water quality, hydrological regime change (flood mitigation vs. reduced flow), competing uses (irrigation vs. hydropower), GHGs, biological impacts, unintended social, environmental, and political consequences
Groundwater pumping	Proven & popular, generally available, easy to regulate/implement	Salinity, aquifer depletion
Rainwater tanks	Decentralized, readily available irrigation for gardens (popular), reduces water bills	Unpredictable rainfall, Non-potable only, small-scale, energy requirements
Stormwater	Flood reduction	Unpredictable rainfall (uncertainty)
Extension of existing supply	Easy option, status quo maintained	New pipelines/pumps
Demand management and leakage reduction	No major construction required, educates community in the long-term, cost-savings to end user, less pumping/energy costs	Restrictions (fines) not popular, education required, rebate programs may be needed, technological change issues, leakage reduction (staff/monitoring costs)
Dual reticulation/purple pipe non-potable reuse	Reduces overall potable water demand, less treatment required than potable reuse	Non-potable only, may have only seasonal customer demand
Water imports	‘Easy’ (quick-fix) solution,	Pumping requirements, availability of supply

Given the results of the State of the Industry Assessment and the first stakeholder workshop, the draft TBL criteria and the evaluation framework were developed. In addition, a short survey of water utilities in the U.S. and Australia was conducted using Survey Monkey and distributed through WRF to obtain feedback regarding the type and reliability of data likely to be available to utilities (as potential tool users) and their preferred user interface features to allow tailoring of the tool to their needs and expectations. The survey questionnaire and a summary of the main outcomes is provided in Appendix B).

The proposed TBL evaluation methodology and criteria were presented at the second stakeholder workshop held in Long Beach, California on January 24, 2016 with 12 project team members and stakeholders participating in-person and two attending via Skype. The complete list of workshop participants is provided in Appendix A. Representatives from three utilities, Orange County Water District (CA), Tampa Bay Water (FL), and Hampton Roads Sanitation District (VA) gave presentations regarding the relevant water supply issues at their utility. This provided a useful case study context which has allowed the project team to further develop its practical TBL methodology. The project team presented the draft TBL methodology, including the evaluation criteria, the multi-criteria decision analysis (MDCA) framework, and use of the EVAMIX scoring method, as described in this report. The participating utilities present at the workshop were very supportive of the draft methodology but also raised some concerns and provided positive feedback along with suggestions for additional indicators to be included in the final list of TBL criteria. It was at this point when the team decided, given the requests for specialised criteria which may not be useful for all utilities, that the tool needed to offer the option for the user to add other criteria which was included in WaterSET.

Given input from the project's participating utilities, the Project Advisory Committee (PAC), and the utility survey, the project team finalized the TBL methodology and developed and tested the computerized tool using inputs from utility partners. This aspect of the study was the most challenging as a significant amount of data and information, including capital and operational cost curves for 74 unit processes, were collected, compiled, and incorporated into the computer model (coded in Matlab) so that the final packaged Excel tool would remain as user friendly as possible while providing input flexibility and useful and relevant results.

As a final evaluation of the usefulness and applicability of the TBL Methodology and Tool, case studies of two U.S. utilities were conducted, one pertaining to the western region of the U.S. and the other to the southeastern region.

Feedback from the case study utilities and other project partners were used to refine the tool to create a fully customizable and user-friendly spreadsheet-based computer application that can be used in any geographic region in the U.S. or Australia and also accommodate additional water supply options.

1.4 WaterSET Model as a Key Deliverable

The outcome of Reuse-14-03 is an ambitious first attempt to develop a sophisticated and generalizable quantitative modelling framework capable of computing impacts across multiple TBL indicators for a wide range of user-specified treatment trains. The user interface portion of the model is packaged as a compact, user-friendly Excel spreadsheet tool enabling water utilities to carry out their own TBL assessments and select the best WSO configurations for their own purposes. The computational engine and all underlying functions have been coded in Matlab to ensure high performance and full automation, though a Matlab license is not required or user to access and run WaterSET. All model inputs, cost curves, cost indices and environmental intensity data may be updated at any stage to ensure the longevity of the tool.

This report presents the conceptual and theoretical framework underpinning the "Water Supply Evaluation Tool" called "WaterSET" which is an Excel-based user-friendly computer model developed during this project. The modelling framework incorporates economic and environmental input-output analyses, lifecycle cost analysis, and social impact analysis into a triple bottom line multi-criteria decision analysis of water supply options. This report includes a description of the trip a user manual (section 3.5) that contains step-by-step guidance on the implementation of WaterSET with definitions of all the input variables and outputs used for comparing alternative scenarios. Easy instructions on how to install and operate the tool are provided in Appendix C.

1.5 Benefits of WaterSET versus Traditional TBL Approaches

The WaterSET Framework provides a more comprehensive and versatile TBL assessment building upon more traditional TBL approaches employed in recent years in the assessment of water supply options in the U.S. and Australia (seen previously in Atkins et al. 2010; Stratus Consulting 2011; YVW 2011; Schulz et al. 2012; Raucher 2013; SFPUC 2013; LGNSW 2014; Schimmoller et al. 2015). The benefits of WaterSET are summarised as follows.

1. WaterSET enables a comprehensive comparison between different WSOs as it carries out an analysis at the unit process level, allowing full customization of treatment processes, pumping, onsite fuel use, and other components of a WSO.
2. Instead of focusing exclusively on direct impacts of the on-site processes, WaterSET can concurrently estimate and report the direct impacts and the indirect impacts embodied along the entire chain of inputs (including products imported from overseas) used to create, use and maintain the on-site processes.
3. Unlike many conventional TBL studies, which make considerable assumptions when assigning monetary values to all environmental and social impacts, WaterSET generates values expressed in the appropriate unit (e.g., quantifying CO_2 emissions when referring to the carbon footprint or tons of waste when referring to waste). This allows for benchmarking as well as an appreciation of trade-offs between indicators for each of the water supply options. The user still has the option to aggregate criteria into a common metric with the use of MCDA.
4. WaterSET can provide visualizations such as simple radar diagrams (as those currently available in the spreadsheet tool) the may be used to facilitate public communication and outreach. Further visualisations could also be built into the tool in the future.
5. WaterSET is perfectly suited to the production of a generalized TBL tool, since the underlying equations and code can be applied and further customized for any WSO or locality. Inputs can be readily customized by decision makers who do not need to have any knowledge of the underlying mathematical operations to generate results relevant for their purposes. An apt demonstration of the reliability and adaptability of WaterSET is Carnegie Mellon's long-standing on-line Environmental Input Output (EIO)-LCA tool which estimates economic activity, water withdrawals, and material and energy resources used by different economic activities in the U.S.[2]
6. WaterSET calculates impacts and benefits on the basis on the basis of disaggregated unit process cost curves. This allows the user to fully customise their WSOs and also ensures compatibility with the U.S. Environment Protection Agency's development of detailed Work Breakdown Structure-Based Cost Models for drinking water treatment technologies (Rajiv et al. 2013; U.S. EPA 2014).

[2] http://www.eiolca.net/

CHAPTER 2

Triple Bottom Line (TBL) Criteria

A critical factor in triple bottom line assessments is the selection of decision making criteria and the weighting of these criteria as deemed appropriate. These criteria should span the potential economic, environmental, and social impacts of the various options under consideration. Additionally, each criterion should be unique from the others (i.e., one criterion should not directly correlate with other) to ensure that individual impacts are not being taken into account multiple times.

2.1 Choice of Criteria

The framework used to underpin the WaterSET TBL model is designed to allow the user to include a variety of criteria in the evaluation of WSOs. WaterSET incorporates a host of criteria that are considered by water supply planners and decision makers to represent key benefits, costs, or constraints that have the potential to impact the economic, technical, social, or environmental feasibility of a WSO. The most popular of the criteria is life cycle cost per unit of water produced – the lower the cost per unit, the more desirable the project. The use of WaterSET facilitates consideration of many other important criteria that can identify the most desirable WSOs. The user assigns weights to each criterion to indicate its relative importance – the larger the weight, the more important the criterion. Weights set to zero indicate that those criteria are not included in the WSO evaluation.

The criteria chosen for WaterSET were based on utility input obtained during the two project workshops, the literature review, and the expertise of the project team in evaluating WSOs. The criteria reflect one of three TBL categories: economic, environmental, and social.

2.1.1 Economic Criteria

The economic criteria included in WaterSET are summarized in Table 2-1 and address:

1. WSO cost-efficiency;
2. Amount of water produced;
3. Percent of cost paid by outside entities;
4. Cost of imports as a percent of total cost;
5. Variable cost percentage of total cost;
6. Direct and indirect impacts of WSO cost on U.S. and local income per unit of water produced; and
7. Number of jobs created in the U.S. during WSO construction and operation per unit of water produced.

The first column of the table is a brief description of the criterion. The second column indicates whether the criterion has a positive or negative impact on the WSO evaluation score. A positive distinction means that the higher the criterion’s value, the more desirable the WSO. A negative distinction means the higher the criterion’s value, the less desirable the WSO. The third column indicates whether the criterion is a Qualitative (L) or Quantitative (T) value and whether the criterion value is provided by the WaterSET Model (M) or is provided by the User (U). The fourth column provides additional definition and measurement of the criterion.

Many of these criteria, including cost, income, and tax revenue, are measured on a "per unit of water produced" basis to allow a fair and harmonized comparison of criteria values among a variety of WSO production capacities. This unit approach, similar to the commonly used concept of unit cost, is known as a functional unit in LCA, where each functional unit of water is typically either 1m^3, 1000 gallons, or 100 acre-feet of water depending on the study (Stokes and Horvath 2006; Zhou et al. 2014). For the purposes of the present tool we adopt 1,000 gallons of treated water as the functional unit.

The WSO cost-efficiency criterion is calculated as the net present value of costs over the useful life of the WSO divided by the amount of water produced. The costs include capital costs and operations and maintenance costs. It is a quantitative value that measures the cost of water supplied by the WSO per unit of water produced. The larger the value, the less desirable the WSO. This value is calculated by the WaterSET model using information supplied by the user with regards to unit processes, chemicals, and other fixed and variable costs. Where the user has full knowledge and confidence in their own cost values, they may be entered into WaterSET.

Table 2-1. WaterSET Economic Criteria.

Criterion	Positive or Negative	Qualitative (L) or Quantitative (T) / Model (M) or User (U) Provided	Definition / Measurement
(1)	(2)	(3)	(4)
Economic Impacts to the Utility and Rate Payers			
Lifecycle cost of WSO to utility per unit of water produced	Negative	T / M	Present value of costs over useful life of WSO divided by water produced. Cost includes Capital, O&M.
Average annual amount of water produced	Positive	T / U	Annual average million gallons per day (MGD) measures ability of WSO to supply needed water
Percent of capital cost to be paid by outside entities	Positive	T / U	Measures extent to which cost is shared with others thus reducing financial impact to customers
Cost of imported capital and O&M as percent of total cost	Negative	T / M	Annualized cost of imported capital, operation and maintenance goods as a percent of total capital, operation and maintenance cost
Variable cost percentage of total cost	Positive	T /MU	% of annualized capital and O&M cost that is variable over 1 to 3 year period (chemicals, energy and labor). Captures financial flexibility of WSO.
Economic Benefits & Costs to Society			
Impact of WSO construction and operation on U.S. resident income per unit of water produced	Positive	T / M	Income includes wages, salaries, proprietor income, profit; Represents contribution of WSO to national income
Number of jobs created in the U.S. during WSO construction and operation per unit of water produced	Positive	T / M	Income includes wages, salaries, proprietor income, profit; Represents contribution of WSO to local income

The amount of water produced is also included as an economic criterion for those evaluations where WSOs that produce large quantities of water are more desirable than smaller WSOs. The value for each WSO is a quantitative value provided by the user in annual average million gallons per day (MGD). This criterion has a positive impact on the WSO's evaluation score.

The percent of capital cost to be paid by outside entities measures the extent to which the WSO cost would be shared with others thus reducing financial impact to customers. Values for this criterion are quantitative and entered by the user. The larger the value, the more desirable the WSO.

The impact of the WSO's construction and operation on national income and local income per unit of water produced is an indicator of the extent to which the associated goods and services are supplied domestically versus imported from other countries. Also, the more expensive a WSO per unit of water produced, the greater the domestic income that will be generated, all else equal. Income includes wages, salaries, proprietor income, and profit before taxes. Both direct and indirect income are included in these criteria. These criteria do not measure the economic activity generated as a result of the water supplied to users.

Direct income arises from activities directly associated with construction and operation of the WSO. Hence a utility purchases goods and services from the direct firms including contractors, electricians, manufacturers, households, and engineers. These purchases provide direct jobs and income locally and nationwide. Indirect impacts are jobs and income generated as the direct firms purchase from other firms the inputs needed to produce the goods and services sold to the utilities (upstream in the supply chain). WaterSET provides the direct and indirect income to households and businesses in the United States. Local income impacts need to be provided by the user but can easily be input into the model and incorporated into the WSO evaluation. Both criteria are quantitative and have a positive impact on the WSO's evaluation score.

To address the financial flexibility of the WSO, the user may want to include as a criterion the variable cost as a percent of total annualized cost. The intent here is to assess to extent to which the WSO is financially reversible in that a WSO with costs dominated by variable costs is more easily reversible from a financial standpoint than a WSO dominated by fixed costs and debt service. Variable costs are those that can be adjusted over a one to three year period such as labor, chemicals and energy. Total annualized cost is the annualized capital and non-annual recurring cost plus annual operations and maintenance cost. This value is quantitative, calculated by the model, and has a positive impact on the WSO's evaluation score.

The annualized cost of imported capital, operation, and maintenance goods as a percent of total annualized capital, operation and maintenance cost is another measure of the extent to which the WSO relies on goods imported from other countries. It is a quantitative value calculated by the model and has a negative impact on the WSO's score. This criterion is not necessary if the U.S. income indicator is one of the criteria used in the evaluation. The impact of the WSO on direct and indirect U.S. income is the other indicator of WSO reliance on imported goods.

WSO construction and operation may have an impact on the collection of local tax revenue. If this is the case, then the criterion that measures the impact of the WSO on Local Tax Revenue per unit of water produced may be important to the WSO evaluation. It is a quantitative value provided by the user and has a positive impact on the WSO's score.

2.1.2 Environmental Criteria

The environmental criteria included in WaterSET are summarized in Table 2-2 and address:

1. Carbon footprint in kg of Equivalent Carbon Dioxide per unit of water produced.
2. Water footprint in cubic meter of water required to produce a unit of water.

3. Eutrophication potential in kilograms of Nitrogen Equivalent per unit of water produced.[3]
4. Ecotoxicity potential in kilograms of DCB (1,4-Di-chloro-benzene) Equivalent per unit of water produced.[4]
5. Land footprint in acres of land used for WSO site per unit of water produced.

The carbon footprint measures the total amount of greenhouse gas emissions generated during the construction and operation of the WSO. It is measured in terms of the Equivalent CO_2 emitted per unit of water produced. The water footprint measures the amount of water needed to produce a unit of water and does not include the water produced. The impact of the WSO's construction and operation on the pollution of ecosystems is measured by the eutrophication potential and the ecotoxicity potential per unit of water produced. These quantitative values include both the direct and indirect effects of the supply chain. The values are computer by WaterSET and have a negative impact on the WSO's evaluation score.

Table 2-2. WaterSET Environmental Criteria.

Criterion	Positive or Negative	Qualitative (L) or Quantitative (T) / Model (M) or User (U) Provided	Definition / Measurement
(1)	(2)	(3)	(4)
Carbon footprint per unit of water produced	Negative	T / M	Carbon footprint in tons of Equivalent Carbon Dioxide (kg CO2-e) per unit of water produced
Water footprint per unit of water produced	Negative	T / M	Water footprint in gallons of water required to produce a unit of water, not including the water produced
Eutrophication potential per unit of water produced	Negative	T / M	kg N equivalent measures impact of WSO construction and operation on pollution of ecosystems
Ecotoxicity potential per unit of water produced	Negative	T / M	kg DCB equivalent measures effect of WSO construction and operation on pollution of ecosystems per unit of water produced
Land footprint per unit of water produced	Negative	T / U	Hectares measures the opportunity cost of land needed to site the WSO

The amount of land needed to site the WSO per unit of water produced is included as a criterion that measures the opportunity cost of land. The larger the land area needed per unit of water produced, the less desirable the WSO relative to WSOs that have smaller footprints. This quantitative value is provided by the user.

2.1.3 Social and Other Qualitative Criteria

The social and other qualitative criteria included in WaterSET are summarized in Table 2-3 and address the following items with descriptions provided after the table:

1. Effect of WSO construction and operation on human health per unit of water produced.[5]
2. Drought resilience of the WSO.
3. Potential public acceptance of the WSO.
4. Further social benefits of the WSO.
5. Implementation risk of the WSO.

[3] This is a commonly used LCA indicator of eutrophication potential (Schulz et al. 2012).
[4] This is a commonly used LCA indicator of freshwater and marine ecotoxicity (Lundie et al. 2007).
[5] This is quantified using human toxicity potential (HTP), a commonly used LCA indicator that reflects impacts on human health associated with chemical releases to the environment (Hertwich et al. 2001).

6. WSO Pollution Impacts.
7. WSO Waste Disposal Impacts.
8. WSO Construction Impacts.
9. WSO Operational Impacts.

Table 2-3. WaterSET Social and Other Criteria.

Criterion	Positive or Negative	Qualitative (L) or Quantitative (T) / Model (M) or User (U) Provided	Definition / Measurement
(1)	(2)	(3)	(4)
Effect of WSO construction and operation on human health per unit of water produced	Negative	T / M	Human toxicity potential (HTP), a commonly used LCA index that reflects the potential harm to human health of chemicals released into the environment related to the construction and operation of the WSO.
Drought resilience	Positive	L / U	Measures impact of WSO on the frequency and extent of water shortages and the extent to which the WSO facilitates a drought-proof water utility. Suggested scoring system provides values of 0 to 4 points.
Potential public acceptance of the WSO	Negative	T / U	Budget in dollars or time in months required to provide the education and outreach needed to obtain public acceptance of the WSO.
Further social benefits	Positive	L / U	Measured by counting the number of listed benefits that are created by or directly result from the WSO. WaterSET allows the user to indicate whether or not each of eleven individual benefits should be counted for the given WSO.
Implementation risk	Positive	L / U	Measures the degree to which the WSO can be built and operated successfully in the study area. Suggested scoring system provides values of 0 to 4 points.
WSO Pollution Impacts	Negative	L / U	Pollution of local air, land, and/or waterways may negatively impact aesthetics, cause loss of recreational opportunities and/or harm ecosystems. Value for this criterion is on a scale from 1 to 10, with 10 being the worst/highest level of impacts and 1 being the lowest level of impacts.
WSO Waste Disposal Impacts	Negative	L / U	Waste disposal could harm local amenities, including aesthetic impacts of landfilling and waste transport. Value for this criterion is on a scale from 1 to 10, with 10 being the worst/highest level of negative impacts and 1 being the lowest level of negative impacts.
WSO Construction Impacts	Negative	L / U	Impacts of construction on local amenities, including noise, odor, traffic congestion, and road closures. Value for this criterion is on a scale from 1 to 10, with 10 being the worst/highest level of negative impacts and 1 being the lowest level of negative impacts.
WSO Operational Impacts	Negative	L / U	Impacts of WSO operation on local amenities, including noise, odor, and commuting /transportation. Value for this criterion is on a scale from 1 to 10, with 10 being the worst/highest level of negative impacts and 1 being the lowest level of negative impacts.

The **Effect of WSO construction and operation on human health** per unit of water produced is provided by the WaterSET model. It measures Human toxicity potential (HTP), a commonly used LCA index that reflects the potential harm to human health from chemicals released into the environment as a result of the construction and operation of the WSO. It has a negative contribution to the WSO's evaluation score.

The Drought Resilience criterion measures the impact of the option on the frequency and extent of water shortages and the extent to which the option facilitates a drought-proof water utility.

Note regarding drought resilience and water reuse: Because the amount of reclaimed water available is based on the amount of potable water used, a direct potable reuse project would not always be drought-proof on its own. This is because potable water use can vary depending on the need for increased irrigation caused by drought and the utility's response to water shortages through water pricing and water use restrictions. The net effect of these factors could be a reduction in the amount of reclaimed water available. However, its use in conjunction with other water supply sources and demand management programs could significantly reduce the impact of weather and climate on water supply.

The scoring for the Drought Resilience criterion is as follows.

Estimate the amount of water that would be produced from the WSO during drought conditions relative to the amount that could be produced from the WSO during years of "average" precipitation. Define drought as that which occurs under a one-in-ten precipitation year which is the lowest precipitation that statistically occurs on the average of once during a ten-year period. The value for this criterion can be obtained as follows.

0 Points = During drought conditions, the WSO can produce (or save in the case of water conservation/leak detection) no more than 25% of average year expected water production (or savings)

1 Point = During drought conditions, the water supply option can produce (or save) from 26% to 50% of average year expected water production (or savings)

2 Points = During drought conditions, the water supply option can produce (or save) from 51% to 75% of average year expected water production (or savings)

3 Points = During drought conditions, the water supply option can produce (or save) from 76% to 99% of average year expected water production (or savings)

4 Points = During drought conditions, the water supply option can produce (or save) more than 99% of average year expected water production (or savings)

Potential Public Acceptance of a WSO can be changed through education and outreach. This criterion measures the extent to which the utility will need to provide public education and outreach in order to obtain public consensus that the option is an acceptable method of providing the community with potable water.

WaterSET allows for two measures of potential public acceptance. The first measure is the estimated budget in dollars that would be needed to provide the public education and outreach necessary to obtain sufficient public support for developing the WSO. The estimated budget should include the cost of utility personnel, materials, services, and the contracting of private firms as needed. The second measure is the number of months that it is expected to take to obtain sufficient public support using the budgeted public education and outreach efforts. The values attributed to this criterion should not only reflect the budget or time required for outreach to the general public, but also that required for communication and demonstrations throughout the permitting process. Alternative water supplies that are infrequently put into practice may be less subject to immediate acceptance by the public, as well as by regulators, with both parties requiring information and demonstrations for approval. If the WSO does not require any public education or outreach in order to be acceptable, then the value would be zero for each of these measurements. Either measurement may be used to assess potential public acceptance.

The **"Further Social Benefits"** criterion measures the social benefits provided by the WSO in addition to its value in providing a water supply. It is measured by counting the number of benefits listed below that are created by or directly result from the WSO. WaterSET allows the user to indicate whether or not each of eleven individual benefits should be counted for the given WSO.

a. The WSO provides the utility and the community with full control of its water supply through regulations, investments, and/or agreements.

b. The WSO provides a needed means of wastewater effluent disposal.

c. The WSO improves recreational quality or increases recreational opportunities.

d. The WSO improves flood control capabilities within the community.

e. The WSO directly increases the efficiency of water use.

f. The WSO controls saltwater intrusion.

g. The WSO will directly facilitate increases in tourism in the regional area.

h. The WSO will reduce soil subsidence and/or improve subsidence management.

i. The WSO will provide resilience from sea level rise and/or natural disasters such as earthquakes, tornadoes, tsunamis, and hurricanes.

j. The WSO will contribute to a net nutrient balance.

k. The WSO will create a natural habitat on previously damaged land.

The **Implementation Risk** criterion measures the degree to which the WSO can be built and operated successfully in the study area. This criterion includes evaluation of the technologic track record of the option that considers whether the technology or program has been successfully implemented elsewhere. Knowing that a technology or program has been successfully implemented elsewhere in a similar application not only demonstrates its viability, it also provides information regarding the extent to which the technology or program can be customized to site-specific conditions. This criterion also considers the extent to which studies have demonstrated the likelihood of the WSO's success. The evaluators are asked to consider issues specific to the WSO including, for example, siting issues, waste disposal issues, recovery issues, and technology issues.

There are four aspects to consider when scoring this criterion: 1) whether a technology and/or program has been implemented in other similar situations; 2) whether the technology or program was successful; 3) whether studies have shown that it is likely to be successful under this application, and 4) whether or not there are specific unresolved issues that may hinder the success of the WSO. The scoring for this criterion is as follows:

0 Points = The technology or program has not been successfully implemented elsewhere in similar applications and the technology / program is not likely (< 50% probability) to be successful under this application.

1 Point = The technology or program has not been successfully implemented elsewhere in similar applications but studies have shown that it is likely (> 50% probability) to be successful under this application.

2 Points = The technology or program has been successfully implemented elsewhere in similar application, but further study is needed to assess one or more specific unresolved issues that may hinder the success of the Option.

3 Points = The technology or program has been successfully implemented in a relatively small number of similar applications and is likely (> 50% probability) to be successful under this application.

4 Points = The technology or program has been implemented in many similar applications and has demonstrated success and is likely (> 50% probability) to be successful under this application.

WSO Pollution Impacts measures the expected pollution impacts (negative impacts) of the WSO. Pollution of local air, land, and/or waterways should be taken into consideration. Pollution may negatively impact aesthetics, cause loss of recreational opportunities, and/or harm ecosystems. This is a qualitative score where the value for this criterion is on a scale from 1 to 10, with 10 being the worst/highest level of pollution impacts and 1 being the lowest level of pollution impacts.

WSO Waste Disposal Impacts measures the expected waste disposal impacts (negative impacts) of the WSO. The user should consider the impact of waste disposal on local amenities, including aesthetic impacts of landfilling and waste transport. For WSOs that produce significant quantities of residuals and/or brine the cost to manage these waste products can be included in this criterion or assigned as a new criterion (see below). This is a qualitative score where the value for this criterion is on a scale from 1 to 10, with 10 being the worst/highest level of negative waste disposal impacts and 1 being the lowest level of negative waste disposal impacts.

WSO Construction Impacts measures the expected construction impacts (negative impacts) of the WSO. The user should consider impacts of construction on local amenities, including noise, odor, traffic congestion, and road closures. This is a qualitative score where the value for this criterion is on a scale from 1 to 10, with 10 being the worst/highest level of negative construction impacts and 1 being the lowest level of negative construction impacts.

WSO Operational Impacts measures the expected negative impacts of operating the WSO. The user should consider impacts of WSO operation on local amenities, including noise, odor, and commuting/transportation. This is a qualitative score where the value for this criterion is on a scale from 1 to 10, with 10 being the worst/highest level of negative operational impacts and 1 being the lowest level of negative operational impacts.

New Criteria may be added by the user. The information required is a user-input Criterion Name, Criterion Classification as qualitative or quantitative, and whether the criterion is positively or negatively correlated with benefit. If a high value for the criterion is seen as desirable, then then criterion is positively correlated with benefit. For example, the amount of water produced is considered to be positively correlated with benefit. If a high value for the criterion is seen as undesirable, then the criterion is negatively correlated with benefit (e.g., lifecycle cost per unit of water produced).

While not exhaustive, the selected list of criteria captures key considerations often made in water resources-related decision making. Great caution was exercised in developing a comprehensive list with several objectives in mind: 1) to avoid the common pitfall of double-counting project elements by using criteria that may account for similar impacts (e.g. energy and greenhouse gases; life cycle cost and capital cost), 2) to incorporate feedback from workshops and the PAC, and insights gained via an in-depth review of recent water supply MCDA approaches in the literature (Marques et al. 2015; Rathnayaka et al. 2016), and 3) to comprehensively capture aspects especially relevant to DPR and water reuse in general, such as social acceptability (Dolnicar et al. 2010; Dolnicar et al. 2011).

2.2 Combining Criteria and Choosing Between Options

All individual criteria presented in the previous section are available to the user in their native units. However, as previously explained in Section 1.2.3, MCDA is an important component of decision-making in cases where the user is faced with multiple and diverse indicators. Through MCDA, WaterSET offers the option to obtain a single aggregate score with which to compare the different WSOs under consideration. However, it is important to stress that the goal of using MCDA is not simply to aggregate the results, but to allow the user to understand the impacts and nuances caused by variations in criteria weighting, so as to provide further insight for the final recommendation. In this way, an uncertain but highly weighted criterion that appears to significantly impact the final score, may become a priority for further data collection by the water utility.

2.3 The Impact of Uncertainty on Decision Making

Uncertainty plays a role in triple bottom line evaluations, as it pertains to user inputs and background datasets. This section speaks to uncertainty in the WaterSET framework and how the sensitivity of results to uncertainty may be evaluated within the tool.

2.3.1 Uncertainty in the WaterSET Framework

Uncertainty is a major hindrance to decision-making. Any framework or model must openly acknowledge the major sources of uncertainty to ensure that the user is fully aware of potential pitfalls and nuances in the final results but also, more importantly, to enable tailored data collection and necessary improvements that will improve the framework/model and better inform decision-making. Choosing between different WSOs inevitably involves several major sources of uncertainty:

- Yield uncertainty (this is primarily the case for rainfall-dependent WSOs).
- Cost and financial uncertainty.
- Demand uncertainty in certain fast-growing or rapidly changing areas.
- Lack of data which results in criteria that are not well quantified.
- Uncertainty in model outputs (e.g., LCA) and source datasets used in the calculation of quantitative variables.
- Subjectivity when it comes to assigning scores for qualitative variables or weighting criteria.

The WaterSET Tool is flexible in that it allows the user to test many different combinations and sizes of unit processes, consider the individual and combined impacts of key water supply inputs, and perform MCDA using any combination of weights. An important feature of the tool is the ability to vary the flow rate in relation to the capacity for any given WSO. This is extremely relevant in cases where comparisons between a conventional (climate-dependent option) and a non-conventional option, which in most cases guarantees a certain yield, is being carried out.

A report by the National Research Council (2008) quantitatively demonstrates the use of constant-reliability-benefit unit costs. The report concludes that, under certain future climatic assumptions (e.g., high yield uncertainty) where a higher capacity is required to guarantee a certain flow rate, an advanced treatment option like DPR can actually present the best supply augmentation option from a reliability and an economic perspective. Ultimately, the choice in many cases is not simply between two WSOs but in finding what the optimum water supply mix may be for a particular location. This may guard against uncertainty as different WSOs offer different advantages (e.g., resilience to drought or seasonality in non-conventional options, or lower cost of operation during wetter years for conventional options) and it is by combining these in the right proportions that utilities can ensure optimum TBL performance.

Often there is uncertainty in choosing appropriate criteria and concern regarding whether or not prioritising one criterion over another will affect the outcome. MCDA allows tool users to evaluate the impact of criteria prioritization on the scoring and ranking of WSOs. Throughout this project the utility partners and other utilities were consulted through workshops and surveys to ensure that the criteria included in WaterSET are sufficiently comprehensive yet not overlapping to reduce the uncertainty of what criteria to choose and how to measure them. The utility survey was invaluable in determining the types of cost data available to utilities, and the types of costs which pose a data challenge. This feedback was used in model development to identify the inputs and criteria that are defined by the user and those which are internal model variables.

2.3.2 Input and Criteria Uncertainty

In addition to yield uncertainty, important sources of uncertainty come from uncertainty in inputs and model parameters.

2.3.3 Treatment of Uncertainty and Future Research

Screening Analysis using Data Scenarios: Though no automated scenario modelling is currently embedded in WaterSET, the model can be used to implement a screening analysis of uncertainty through multiple runs of alternative scenarios of data, as mentioned above. The screening analysis identifies which sources of uncertainty have the greatest impact on the outcomes of the analysis. Key driver inputs – whose uncertainty most changes the desirability – can be further explored treating specific inputs cells as a distribution of potential values.

Additional research about incorporating uncertainty into MCDA include research by Kaliszewski et al. (2016) and Fenton and Neil (2013). Kaliszewski et al. (2016) extend a multi-criteria framework such as WaterSET by presenting the trade-offs among admissible choices. Fenton and Neil (2013) provide a more formal Bayesian network for a probabilistic analysis of uncertainty. WaterSET can serve as a rigorous basis upon which to build further extensions to better inform decision makers who confront uncertainty.

CHAPTER 3

Triple-Bottom-Line Framework and Methodology Behind WaterSET

This section describes the overall framework and function of WaterSET, including a step-by-step explanation of the model's process flow and the background datasets used for model calculations. Readers are asked to refer to Appendix C for user instructions on how to install and run WaterSET. WaterSET runs in Microsoft Excel but requires installation of 1) an Excel VBA add-in and 2) a free, downloadable Matlab package.

3.1 WaterSET Workflow

WaterSET follows the sustainability framework for Australian water utilities first proposed by Lundie et al. (2006) and further elaborated in Lundie et al. (2008), according to which any sustainability assessment should include six principal phases as explained below:

Phase 1 – Definition of Objectives and Phase 2 – Generation of Options are the responsibility of the water utility and is a pre-requisite for running the WaterSET tool which will guide the utilities through the remaining Phases. Under Phase 1, utilities would consider their future water supply deficits and, under Phase 2, create a shortlist of possible WSOs that address these supply deficits for comparison using WaterSET.

Phase 3 – Selecting Sustainability Criteria is facilitated by WaterSET which prompts the user to select from a list of criteria and weight these criteria according to the priorities of the utility and its stakeholders. The model includes 22 criteria that were developed based on:

- A literature review (Hellström et al. 2000; Balkema et al. 2002; Lundin and Morrison 2002; Schulz et al. 2012; Del Borghi et al. 2013; Marques et al. 2015; Schimmoller et al. 2015; Ries et al. 2016; Thabrew et al. 2017).
- Two utility workshops held February 2015 in Sydney, Australia and January 2016 in Los Angeles, California.
- Feedback from the PAC.
- A survey of utilities conducted during this project aimed at assessing typical utility data availability and factors affecting ease of model use.

WaterSET offers the option for the user to enter additional criteria which could address locally specific environmental or social issues that need to be considered. Because users are expected to weight the criteria, objectivity and transparency should be maintained during this phase (Lundie et al. 2006; Lundie et al. 2008)

Phase 4 – Screening of Options may not be necessary if the WSO shortlist is already limited to a few options. WaterSET is designed to evaluate a total of three alternative WSOs at any given time. To evaluate more than three WSOs, WaterSET can be run for multiples of three WSOs and the results for all WSOs combined into a user-created Excel spreadsheet. A similar procedure may be used to ascertain how different weighting combinations impact the final result.

Phase 5 – Perform Detailed Options Assessments and Phase 6 – Recommend Preferred Alternative are automatically carried out by WaterSET on the basis of user inputs with regards to location, unit processes, chemicals, and conveyance. Based on published recommendations (Lundie et al. 2006; Lundie et al. 2008) , the calculations are carried out using a combination of life cycle cost analysis (LCA), environmentally extended multi-regional input output analysis (EE-MRIO); social impact analysis (SIA), and multi-criteria decision analysis (MCDA). The user is encouraged to conduct sensitivity analyses to obtain a robust outcome.

3.2 WaterSET Overview

The TBL methodology and Excel-based tool has been given the name WaterSET which stands for Water Supply Evaluation Tool. The modelling framework is a Triple-Bottom-Line Input-Output-Based-Lifecycle Analysis that incorporates economic and environmental input-output analyses, lifecycle cost analysis and social impact analysis into a TBL evaluation of water supply options.

A conceptual overview of WaterSET is provided in Figure 3-1. WaterSET begins with a list of WSOs to be evaluated and the input data provided by the user that is used by the model to calculate estimates of capital, operations and maintenance costs. The tool then calculates values for the economic and environmental criteria using an input-output based hybrid - lifecycle analysis (IO-LCA) which relies upon a large environmentally extended multi-regional input-output (EE-MRIO) table of data**.** Onsite fuel consumption and pumping impacts are estimated using process-based LCA – these impacts relate mostly to energy and carbon emissions and are additional to those calculated by the EE-MRIO approach.

The values for the social criteria are calculated separately using the social impact analysis model. All criteria values are then input into the multi-criteria decision analysis (MDCA) which calculates a total score for each WSO and provides a WSO ranking based on the total score.

Each of these components: (a) unit process cost estimation; (b) EE-MRIO and process-based LCA; (c) social impact analysis; and (d) MDCA are depicted in Figure 3-1. A more detailed workflow diagram of these WaterSET components in relation to the tool interface is provided in Figure 3-2.

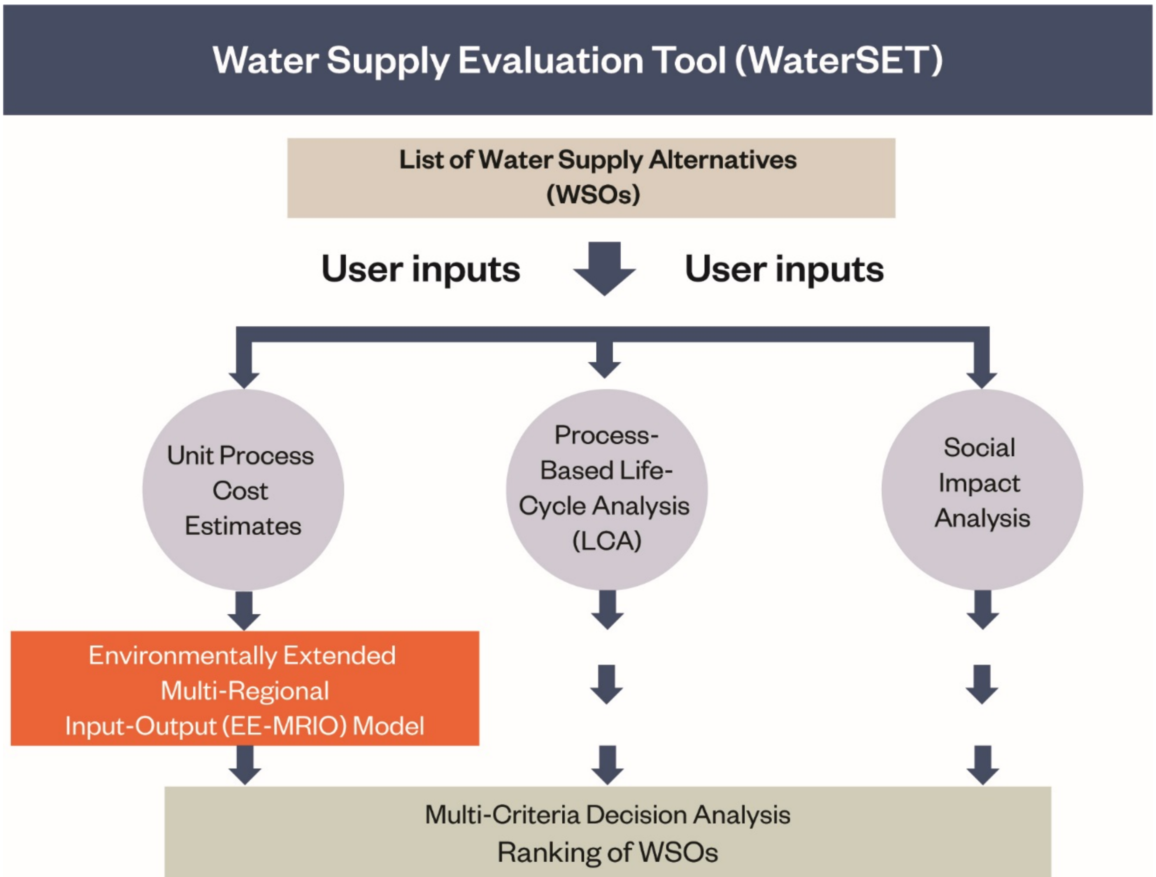

Figure 3-1. Conceptual View of WaterSET.

Descriptions of the major components of WaterSET are provided below:

Process-based Lifecycle Analysis, or process-based LCA, or simply process analysis, accounts for all resource use and environmental releases from on-site production and from a portion of the upstream supply chain of inputs which is typically limited to the direct inputs to the on-site production process (Suh et al. 2004a). The advantage of process analysis is its detail and specificity in the actual physical inputs that create the WSOs and that provide for their operation and maintenance. In this project, process analysis uses utility inputs with regards to onsite fuel use, conveyance and operational energy requirements.

Environmentally Extended Multi-Regional Input Output (EE-MRIO) Model The EE-MRIO model integrates all user inputs to allow computations of direct and indirect economic and environmental impacts associated with the entire supply chain used to construct and operate the WSO. The model is a mathematical simulation of the U.S., Australian, Chinese, and Rest of World economy and the environmental impacts associated with the production of goods and services.

The economic impacts are the income and employment created as the utility purchases the goods and services needed to construct, operate, and maintain the WSO throughout its useful life. These purchases generate direct and indirect income and employment. One of the economic criteria of WaterSET is the impact of the WSO on income to U.S. residents. This value is estimated by the EE-MRIO-LCA Model as the direct and indirect income generated from the WSO that accrues to those who live in the U.S. One of the social criteria of WaterSET is the impact of the WSO on U.S. employment as measured in full-time-equivalents. This value is estimated by the EE-MRIO Model as the direct and indirect U.S. employment generated from the WSO.

Direct income and employment are generated as the utility pays firms to build and equip the WSO and as the utility hires employees and purchases chemicals and materials to operate and maintain the WSO. Indirect income and employment are generated as the direct businesses purchase goods and services from other businesses in order to produce the goods and services sold to the utility. Even though all of this money is ultimately the cost of constructing and operating the WSO, the money moves as income among many people so the flow of dollars from the utility to labor and to business is counted many times as income.

Environmental impacts are based on physical accounting relationships between each WSO sector's output and the generation of pollutants such as greenhouse gases, toxic air emissions, and water contaminant discharges on a per dollar output or per unit output (e.g. cubic meter of water produced) basis. Relationships between the sector's output and resource consumption such as land and water requirements are also defined. As with economic impacts, the EE-MRIO captures both the direct environmental impacts emanating from the facility's operation and the indirect environmental impacts attributable to the suppliers of inputs. The EE-MRIO model runs for each unique WSO subsector that has been developed using detailed process characterizations and itemized costs generated by the unit process cost estimation model.

Social Impact Analysis (SIA) Although not a modeling tool per se, SIA provides WSO values for additional criteria not captured by either the Process LCA or the EE-MRIO Model but which are deemed important by the utility and its stakeholders. For example, the ability of a WSO to meet water demand during a drought could be an important consideration for some utilities but this "factor" is not evaluated in the EE-MRIO. Factors such as project risk and uncertainty, level of public acceptance, and social benefits such as increased recreational opportunities can be important to a utility's WSO decision (Marques et al. 2015; Schimmoller et al. 2015; Ries et al. 2016). Values are assigned to each criterion depending on the extent to which the WSO achieves or addresses the criterion.

Using the EE-MRIO, Process-Based LCA, and SIA Results in a Multi Criteria Decision Analysis (MCDA) The LCA and the EE-MRIO generate economic and environmental impacts including U.S. resident income and carbon footprint; and the SIA generates values for the social factors. Because these outputs are not in the same quantitative units, they cannot be simply added together for each WSO and ranked by total value. Furthermore, the utility may not place the same weight on each criterion in their decision-making process and these weights will vary from utility to utility. One can conceive of scenarios where the financial considerations almost totally drive the decision making process while in other cases factors such as public acceptance might play a more dominant role in discriminating among WSOs. Hence the MCDA is a two-step process of assigning weights to each criterion and converting the all of the criteria values to a common measurement system that can be aggregated into a total score for each WSO.

The common measurement system used by WaterSET is a prioritization method known as Evaluation of Mixed Data (EVAMIX). This procedure involves a step-by-step process that separates the quantitative criteria from the semi-quantitative criteria and converts each criterion's raw value into a normalized value within the range from zero to one inclusive. Then the WSO's normalized criteria values are compared to each of the other WSO's normalized criteria values by assigning each WSO pair/criterion with a value of 1, 0, or -1 depending on whether the WSO's normalized criterion value is greater than, equal to, or less than the comparison WSO's normalized criterion value. At this point the assigned weight of each criterion is multiplied by the resulting 1, 0, or -1 and the result is summed over all criteria to obtain a "dominance" score for each WSO pair. Additional computations provide an "appraisal" score for each WSO that reflects the overall strength of each WSO compared to the other WSOs. WaterSET provides numerical and graphical presentations of the appraisal score of each WSO and the resulting WSO ranking.

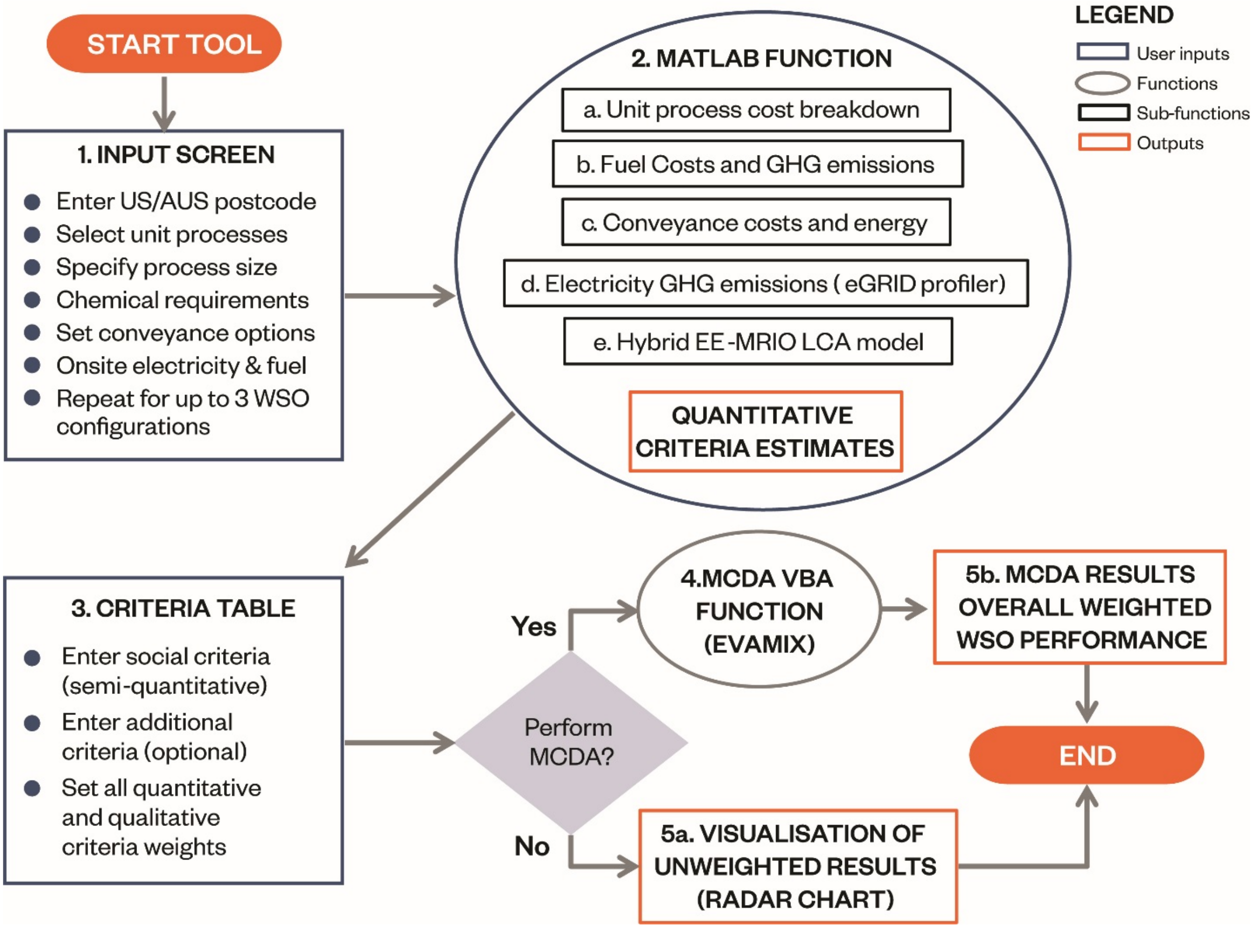

Figure 3-2. WaterSET Step-By-Step Workflow Detailing Inputs, Major Model Functions, and Outputs.

3.3 Combining Input-Output Life Cycle Assessment with Multi-Criteria Decision Analysis

The main core of WaterSET is an EE-MRIO analysis which relies on the economic relationships between sectors in order to quantify and apportion economic and environmental impacts. At its core, the EE-MRIO model employs process lifecycle costs of the WSO, detailed economic and environmental data, and matrix algebra to estimate the full supply chain impacts corresponding to the carbon footprint, the water footprint, the eutrophication potential, the ecotoxicity potential, human health impacts, and U.S. resident income and employment impacts. These calculations take place in real time in response to user-defined inputs and default cost curves from the literature.

The next section explains in more detail the calculations carried out in each of these modelling steps. The main input variables are estimates of all capital costs (CAPEX) and operational expenditures (OPEX) associated with each of the selected WSOs. These costs are estimated in WaterSET based on user-provided inputs and the compiled cost curves and unit cost data collected during this project and incorporate into WaterSET.

3.4 WaterSET Database

The WaterSET model is conceptualized in Figure 3-2 where the flows of sub-model inputs and outputs from the Initial Input Screen to the MCDA Results presentation are shown. The underlying datasets were chosen on the basis of the best available data from the literature and latest industry prices. CAPEX and OPEX cost curves for 74 unit processes are the most important sets of underlying data which, along with user input, form the basis for the calculation of all quantitative criteria. The user may choose the year represented by the estimated costs.

The main Matlab function (See 2 in Figure 3-2) has been coded in a highly flexible manner, allowing for future updates based on either the Engineering News-Record Construction Cost Index (ENR CCI) or locally specific cost curves. The incorporation of locally specific cost curves was deemed to be outside the scope of the current project but constitutes a potentially significant avenue for future framework development.

WaterSET's supplementary files can be downloaded from zip folders at the following link: https://drive.google.com/open?id=0B6HTj-G8iJEHXzNaTHNEWEhLdG8. The following files are provided:

(a) CAPEX cost curves – List of capital cost curves for 74 plants and unit processes. These allow the model to estimate capital expenditure costs associated with each unit process on the basis of the size and quantity specified by the user. The cost curves have been sourced from Kawamura and McGivney (2008) and Sharma et al. (2013) and include a breakdown of costs into excavation and site work, manufactured equipment, concrete, steel, labor, pipes and valves, electrical and instrumentation, and housing (see 'Cost_curves_CAPEX_updated.xlsx' in the 'Final_report_supplementary_spreadsheets' zip folder).

(b) CAPEX cost indices – These are ENR and Bureau of Labor Statistics (BLS) indices for each of the CAPEX categories (see 'CAPEX_cost_indices_updated.xlsx' in the 'Final_report_supplementary_spreadsheets' zip folder). For a detailed explanation of how these cost indices are used see Sharma et al. (2013). Also refer to the 'Indices+Universal Variables' tab in the actual tool.

(c) CAPEX sector concordances – A concordance table which relates each of the CAPEX categories to relevant sectors in the U.S. North American Industry Classification System (NAICS) used in the EE-MRIO (see 'CAPEX_sector_concordance_AUS_US.csv' in the 'Final_report_supplementary_spreadsheets' zip folder).

(d) OPEX cost curves – List of operation and maintenance costs for 74 plants and processes. These allow the model to estimate operational and maintenance costs for each unit process on the basis of the size and quantity specified by the user. The cost curves have been sourced from Sharma et al. (2013) and also allow the breakdown of costs into maintenance material, labor costs, electricity, natural gas and diesel (see 'Cost_curves_OPEX_updated.xlsx' in the 'Final_report_supplementary_spreadsheets' zip folder).

(e) OPEX cost indices – These are ENR and BLS indices for each of the OPEX categories (see 'OPEX_cost_indices_updated.xlsx' in the 'Final_report_supplementary_spreadsheets' zip folder). For a detailed explanation of how these cost indices are used see Sharma et al. (2013).

(f) OPEX concordances – A concordance table which relates each of the OPEX categories to relevant sectors in the U.S. North American Industry Classification System (NAICS) used in the EE-MRIO (see 'OPEX_sector_concordance_AUS_US.xlsx' in the 'Final_report_supplementary_spreadsheets' zip folder).

(g) List of 30 chemicals and chemical types – This lists each chemical and identifies the chemical group that corresponds to an IO sector (see 'Chemical_costs.xlsx' in the 'Final_report_supplementary_spreadsheets' zip folder).

(h) ENR CCI monthly time series (1980-2016) (see 'ENR_CCI_timeseries.xlsx' in the 'Final_report_supplementary_spreadsheets' zip folder).

(i) EPA eGrid power profiler 2012[6] – Used for estimating scope 2 carbon emissions on the basis of energy needs and regional electricity emissions factors (see 'power_profiler_zipcode_tool_2012_v6-0.xlsx' in the 'Final_report_supplementary_spreadsheets' zip folder).

The WaterSET user instructions are provided in Appendix C.

3.5 WaterSET Step-by-Step Explanation

The conceptual model of WaterSET as depicted in Figure 3-2 shows all major inputs, functions and outputs that comprise WaterSET. The numbering of each process reflects the order of operation and corresponds to a sub-section heading in this section. Each of the following sub-sections offers a detailed outlook of the underlying data and calculations at each stage. Please refer back to Figure 3-2 as you read through each sub-section.

Accompanying this report are supplementary spreadsheets containing all background information[7] used in the calculations (see the 'Final_report_supplementary_spreadsheets' zip folder). In the following section, spreadsheets contained in the aforementioned supplementary folder and listed in Section 3.4 above are frequently mentioned in relevant sections.

3.5.1 1. Initial Input Screen

This is where the user enters all of the information used by WaterSET to evaluate each WSO being assessed. This information is used as inputs to the Matlab function allowing the model to compute the quantitative TBL criteria. This screen is available three times (tabs WSO 1 - WSO 3) allowing the user to compare up to three alternative WSOs or WSO variants. The maximum number of WSOs has been restricted to three in order to reduce computation time and to create more intuitive visualizations[8]. Figure 3-3 through Figure 3-6 are screenshots of what the users see as they scroll down the initial input screen and demonstrate some of the options available to the user to customise each WSO.

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[6] See EPA eGRID website for more information.

[7] This background information is static as the user has no access and cannot modify it unlike user-specified inputs that can be modified at will.

[8] Users may perform more comparisons by creating a copy of the spreadsheet.

The user enters a name for the WSO (for example, "DPR with UV-chlorine") and the proposed location of the WSO as defined by the U.S. state and the U.S. zip code. The U.S. State and U.S. zip code information are used to calculate electricity-related CO_2 emissions (2d in Figure 3-2). Next, the user specifies whether the plant is to be built from scratch or whether unit processes will be added to an existing plant[9]. Capacity and plant flow rate are also entered, which allows WaterSET to calculate the costs and impacts per functional unit. The U.S. model uses 1,000 gallons of water production as its functional unit.

The main inputs to the EE-MRIO model are the unit process inputs where the user is asked to specify the size and number of individual units for each process that comprises each WSO. These are used by the model to estimate the CAPEX and OPEX breakdown for each unit process depending on the size specified by the user on the basis of underlying cost curves (see the 'Final_report_supplementary_spreadsheets' zip folder). Since these cost curves do not include chemicals, these must be entered separately. The user can specify dosage in mg/L or lb/day for up to 30 different chemicals (see Figure 3-4).

Additional options are available for the user to enter data that would be used to estimate the costs and environmental impacts associated with energy and residuals disposal such as head loss, number and capacity of pumping station, pump properties, piping materials and costs (including for purple pipe systems), and residuals production (see Figure 3-5 through Figure 3-7). The user needs to enter the WSO service life and the annual real (no inflation) interest (discount) rate to be used in the present value calculations (see Figure 3-7).

Users wishing to use their own cost estimates have the option to enter estimates of CAPEX and OPEX for the WSO thereby eliminating the need for the cost estimating feature of WaterSET. In this case, the costs of all the other WSOs should be estimated in the same manner to maintain consistency among the WSO cost estimates[10]. Onsite electricity production and onsite fuel use can also be recorded in this sheet to allow for a more accurate estimate of total carbon emissions (see Figure 3-7).

The input sheets form the basis for all comparisons between WSOs and may be used to perform sensitivity analysis by modifying different parameters and monitoring the impacts on the final result. In addition to the WSO input sheets, the user can also modify CAPEX and OPEX cost indices (to allow updating of costs), and chemical concentrations and costs in the 'Indices+Universal Variables' tab (see Figures 3-8 and 3-9). The following sub-sections explain in detail how the user-provided input data are processed by WaterSET to estimate the quantitative TBL criteria.

[9] The user is advised to evaluate complete WSOs, not just parts of an existing WSO. If unit processes are to be added to an existing plant, then the user is advised to enter the full costs of the WSO associated with producing the quantity of water that is to be evaluated by WaterSET.

[10] Comparisons between user-specified costs and modelled cost estimates should be avoided.

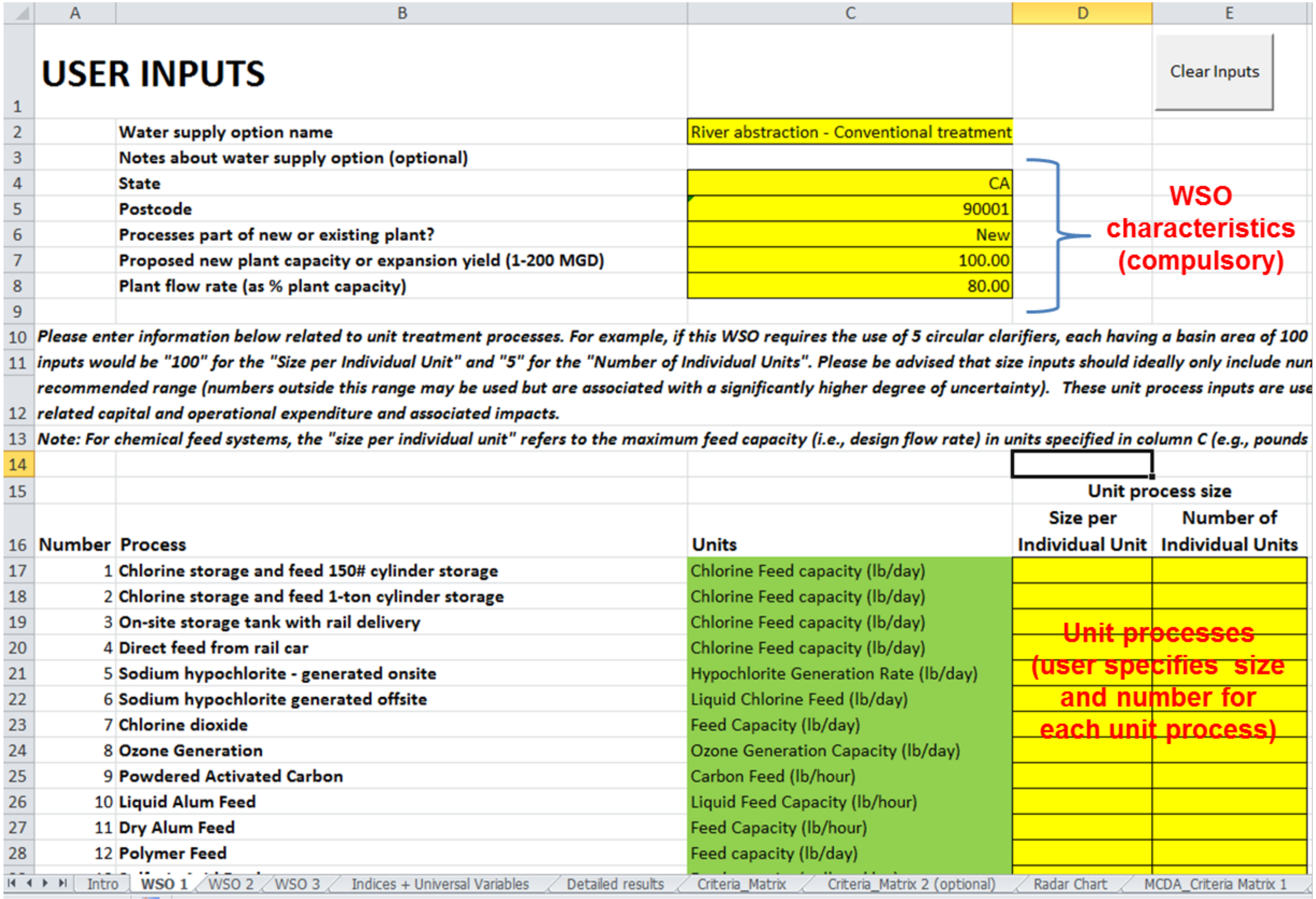


Figure 3-3. Screenshot of Initial WSO User Input Screen Prompting the User to Enter Information Required the Run the Analysis.

Please input information below related to chemical dosing (you have the choice to enter either lb/day or mg/L). These inputs are used to calculate operational requirements.

Chemical Name	Chemical Dose	Units
Caustic Soda (Sodium Hydroxide)		lb/day
Sodium Hypochlorite Liquid chlorine		lb/day
Chlorine Gas		mg/L
Liquid Oxygen (LOX)		lb/day
Liquid Alum Feed - 50% Solution		lb/day
Dry Alum (coagulation) - 48%		lb/day
Polymer (Polydyne SE1179 polymer)		lb/day
Lime		lb/day
Sulfuric Acid - 93% Solution (ph control)		lb/day
Sodium Hydroxide - 50% Solution (ph control)		lb/day
Ferric Chloride Feed - 39% Solution		lb/day
Powdered Activated Carbon		mg/L
Fluoride		mg/L
Phosphate(Phosphoric Acid)		lb/day
Anhydrous Ammonia Feed		lb/day
Aqua Ammonia Feed - 29%		lb/day
Ammonia (chloramines)		lb/day
Chlorine Dioxide		lb/day
Potassium Permanganate - 100%		lb/day
Conditioning of sludge prior to dewatering Polymer		lb/day
Sodium Chloride - 100%		lb/day
PreTreatment w/ Coagulant Addition (Alum)		lb/day
PreTreatment w/ Coagulant Addition (Polymer Alum)		lb/day
Dry Alum Feed (coagulation)		lb/day
Liquid Alum Feed - 50% Solution		lb/day
Antiscalant - 100%		lb/day
Sodium hydroxide - 30%		lb/day
Citric Acid - 50%		lb/day
GAC (Granular Activated Carbon)		lb/day
Hydrogen peroxide - 50%		lb/day

User enters chemical dosage (either as mg/L or lb/day)

Intro | WSO 1 | WSO 2 | WSO 3 | Indices + Universal Variables | Detailed results | Criteria_Matrix | Criteria_Matrix 2 (optional) | Radar Chart | MCDA_Criteria Matrix 1 | MCDA_Crite

Figure 3-4. Screenshot Demonstrating How the User is Asked to Enter Chemical Dosing for Each WSO In Either Units of mg/L or lb/day.

Conveyance: Transmission Mains From Supply to Water Treatment Facility

Please input information related to the conveyance of this WSO to the drinking water treatment facility.

User enters total head (in ft)

Conveyance (Used to estimate energy and cost)			
Estimated total head loss (sum of all major + minor losses + static head)	ft	100.00	
Pump efficiency (default = 0.6)	unitless (0-1)	0.60	
Pumping station(s)		**Capacity**	**Number of stations**
Capacity 1	MGD	50.00	1.00
Capacity 2	MGD	50.00	1.00
Capacity 3	MGD		
Capacity 4	MGD		
Capacity 5	MGD		
Piping type and length	**Material (select one)**	**Length (ft)**	**Diameter (inches)**
Pipe 1	Ductile Iron		
Pipe 2	PVC		
Pipe 3	PVC		
Pipe 4	PVC		
Pipe 5	PVC		
Pipe 6	Ductile Iron		

User enters pumping capacity and stations

User enters piping requirements related to conveyance

Figure 3-5. Screenshot of the Section in Which the User is Asked to Input Information Related to Water Supply Transmission.

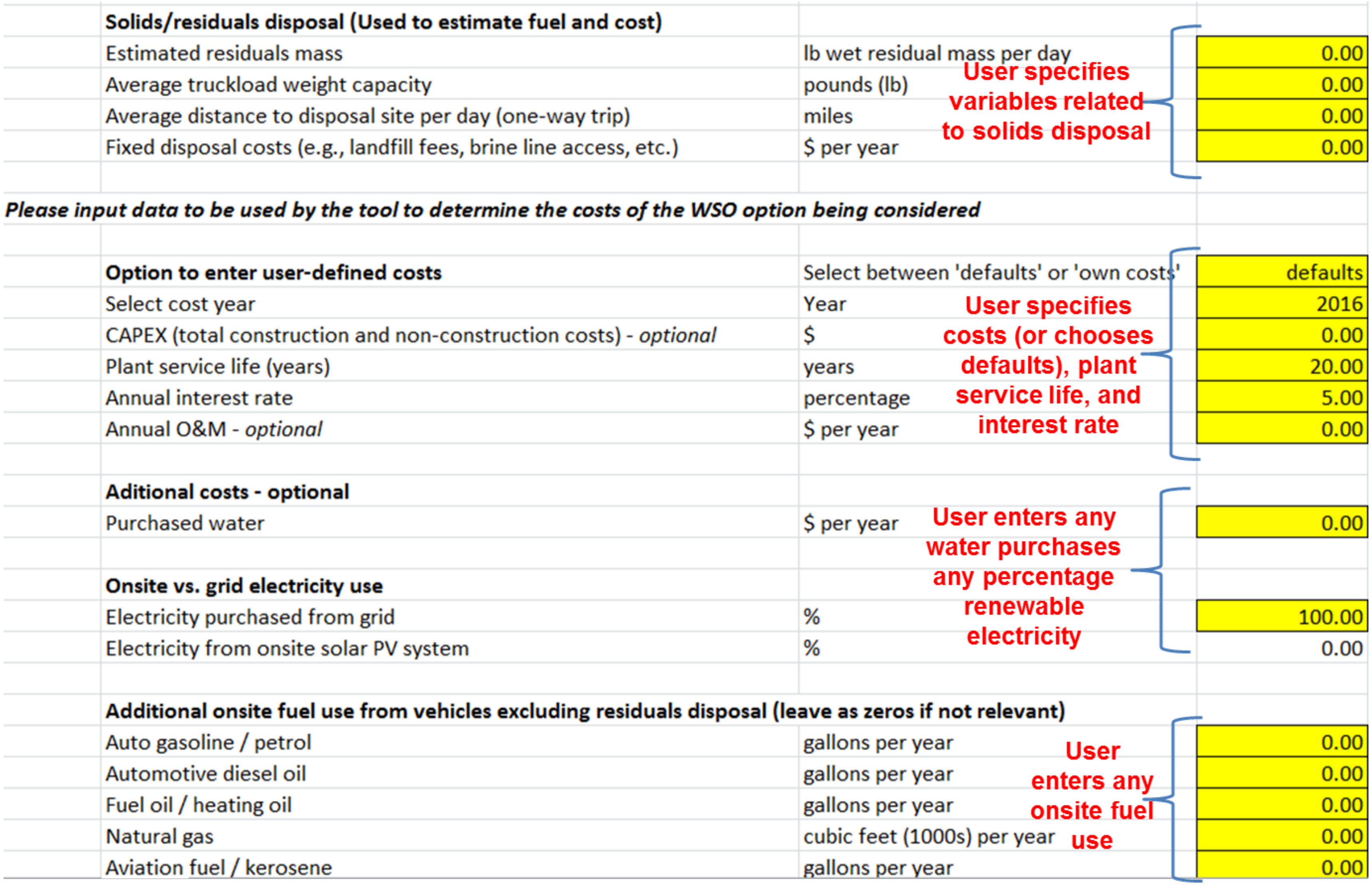
Conveyance: Purple Pipe from Facility to Distribution	Does this apply to this WSO?	No	
Please input information related to a purple pipe (dual reticulation) non-potable reuse system - if not applicable to this WSO choose 'no' above and ignore section			
Conveyance (Used to estimate energy and cost)			
Estimated total head loss (sum of all major + minor losses + static head)	ft		
Pump efficiency (default = 0.6)	unitless (0-1)		
Pumping station(s)		**Capacity**	**Number of stations**
Capacity 1	MGD		
Capacity 2	MGD		
Capacity 3	MGD		
Capacity 4	MGD		
Capacity 5	MGD		
Piping type and length	**Material (select one)**	**Length (ft)**	**Diameter (inches)**
Pipe 1	Ductile Iron		
Pipe 2	PVC		
Pipe 3	PVC		
Pipe 4	PVC		
Pipe 5	PVC		
Pipe 6	PVC		

User enters total head (in ft)

User enters pumping capacity and stations

User enters piping requirements related to purple pipe system

Figure 3-6. Additional Transmission-Related Information for WSOs Involving the Use of Purple Pipe for Non-Potable Reuse.



Solids/residuals disposal (Used to estimate fuel and cost)		
Estimated residuals mass	lb wet residual mass per day	0.00
Average truckload weight capacity	pounds (lb)	0.00
Average distance to disposal site per day (one-way trip)	miles	0.00
Fixed disposal costs (e.g., landfill fees, brine line access, etc.)	$ per year	0.00
Please input data to be used by the tool to determine the costs of the WSO option being considered		
Option to enter user-defined costs	Select between 'defaults' or 'own costs'	defaults
Select cost year	Year	2016
CAPEX (total construction and non-construction costs) - *optional*	$	0.00
Plant service life (years)	years	20.00
Annual interest rate	percentage	5.00
Annual O&M - *optional*	$ per year	0.00
Aditional costs - optional		
Purchased water	$ per year	0.00
Onsite vs. grid electricity use		
Electricity purchased from grid	%	100.00
Electricity from onsite solar PV system	%	0.00
Additional onsite fuel use from vehicles excluding residuals disposal (leave as zeros if not relevant)		
Auto gasoline / petrol	gallons per year	0.00
Automotive diesel oil	gallons per year	0.00
Fuel oil / heating oil	gallons per year	0.00
Natural gas	cubic feet (1000s) per year	0.00
Aviation fuel / kerosene	gallons per year	0.00

Figure 3-7. The User Input Screen for Each WSO Concludes with Fields for Solids Disposal Information, Cost-Related Information, and the Optional Use of Onsite Renewables or Fuels.

	Cost component	Index	Latest value
TOTAL	Total cost	ENR Construction Cost Index (CCI)	10282.00
CAPEX	Excavation and sitework	ENR skilled labor wage index	9927.94
	Manufactured equipment	BLS general purpose machinery and equipment (WPU114)	226.50
	Concrete	BLS concrete ingredients (WPU132)	280.60
	Steel	BLS steel mill products (WPU1017)	174.00
	Labor	ENR skilled labor wage index	9927.94
	Pipes and valves	BLS Miscellaneous General Purpose Equipment (WPU1149)	266.00
	Electrical and instrumentation	BLS electrical machinery and equipment (WPU117)	112.80
	Housing	ENR building cost index (BCI)	5681.63
O&M	Maintenance material	BLS PPI for finished goods (WPUFD49207)	193.70
	Labor cost	ENR skilled labor wage	54.82
	Electricity	US Energy Information Administration	0.10
	Natural gas	US Energy Information Administration	7.58
	Diesel	US Energy Information Administration	2.58
	Gasoline	US Energy Information Administration	2.35
	Fuel oil/heating oil	US Energy Information Administration	2.64
	Kerosene	US Energy Information Administration	1.43

User can specify the latest cost indices to reflect the most recent prices of any of the cost components

Figure 3-8. Users Can Specify the Most Up-o-Date Indices in the 'Indices + Universal Variables" Tab to Allow the Model to Convert All Costs to Their Most Recent Values.

Chemicals	Purity (as a decimal)	Median Cost ($ per lb)
Caustic Soda (Sodium Hydroxide)	0.17	0.25
Sodium Hypochlorite Liquid chlorine	0.12	2.50
Chlorine Gas	1.00	0.13
Liquid Oxygen (LOX)	1.00	0.67
Liquid Alum Feed - 50% Solution	0.09	0.92
Dry Alum (coagulation) - 48%	0.17	0.09
Polymer (Polydyne SE1179 polymer)	1.00	1.75
Lime	1.00	0.09
Sulfuric Acid - 93% Solution (ph control)	0.93	0.64
Sodium Hydroxide - 50% Solution (ph control)	0.17	0.25
Ferric Chloride Feed - 39% Solution	0.39	0.20
Powdered Activated Carbon	1.00	0.92
Fluoride	0.30	0.57
Phosphate(Phosphoric Acid)	0.75	0.48
Anhydrous Ammonia Feed	1.00	0.56
Aqua Ammonia Feed - 29%	0.29	0.16
Ammonia (chloramines)	1.00	0.11
Chlorine Dioxide	1.00	1.69
Potassium Permanganate - 100%	1.00	3.56
Conditioning of sludge prior to dewatering Polyr	1.00	1.75
Sodium Chloride - 100%	1.00	0.06
PreTreatment w/ Coagulant Addition (Alum)	1.00	0.92
PreTreatment w/ Coagulant Addition (Polymer A	1.00	1.92
Dry Alum Feed (coagulation)	0.17	0.09
Liquid Alum Feed - 50% Solution	0.09	0.92
Antiscalant - 100%	1.00	2.25
Sodium hydroxide - 30%	0.17	0.25
Citric Acid - 50%	0.50	0.45
GAC (Granular Activated Carbon)	1.00	1.40
Hydrogen peroxide (H2O2)	0.50	0.42

O & M

User can specify the concentration and cost (per lb) for all chemicals used across all WSOs

Figure 3-9. Users Can Specify Chemical Concentrations and Unit Prices for 30 Commonly Used Chemicals in the 'Indices + Universal Variables' Tab.

3.5.2 2a through d. Matlab Function (Core Model Calculations)

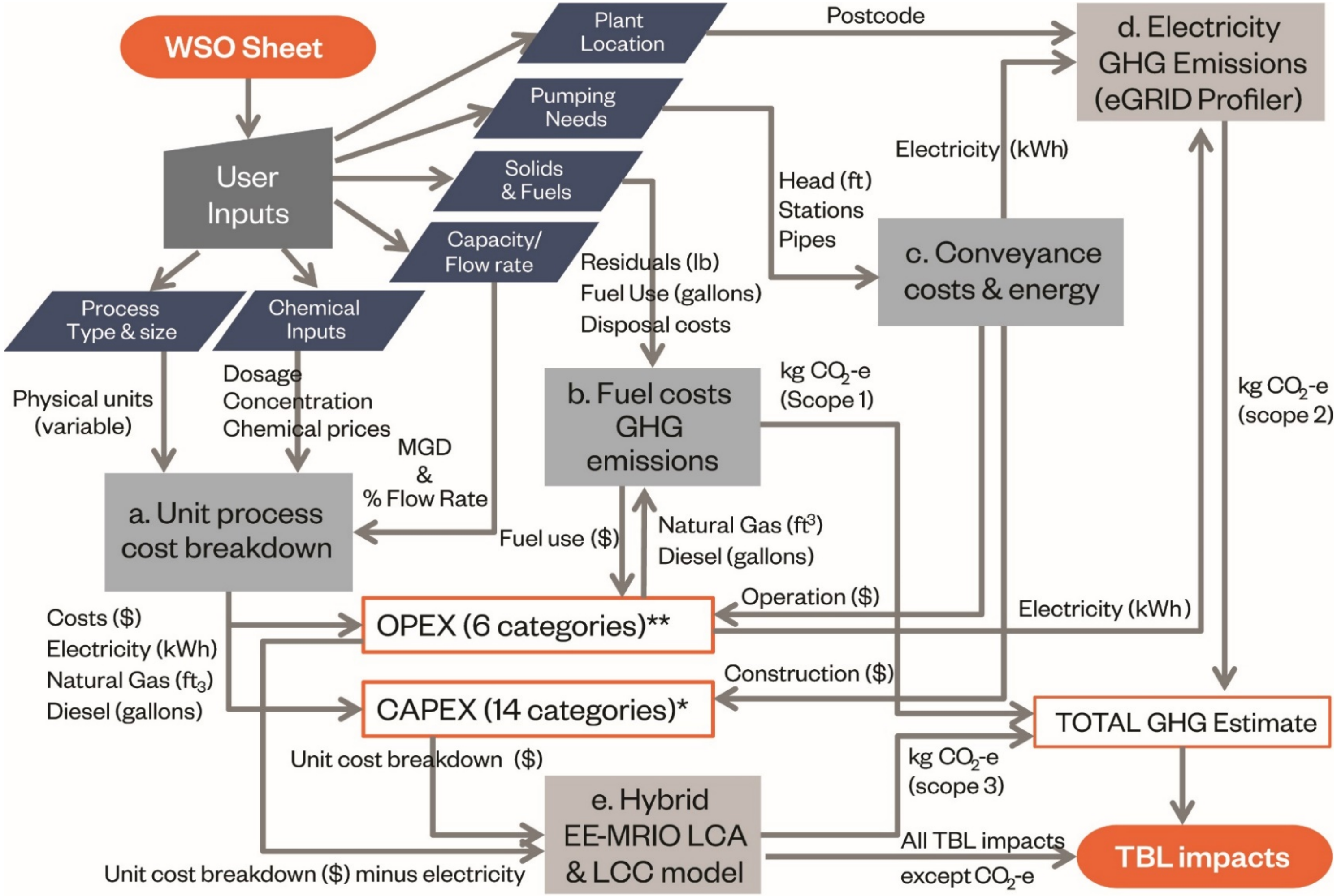
This section provides a technical description of the workflow, calculations, and input datasets used in the core TBL model engine. All operations are performed by the packaged Matlab Visual Basics for Applications (VBA) add-in function and correspond to 2. MATLAB FUNCTION in Figure 3-3 (which lists all individual sub-functions included in the main function). The user needs to install this function alongside the Excel tool spreadsheet (See Appendix C for step-by-step installation instructions.)

Once the user has entered the WSO inputs, the model is ready to run (see Appendix C to learn how to initiate a model 'run'). The main tool function then performs TBL impact calculations for all the quantitative economic, social, and environmental variables. The main function is written in Matlab® code and contains several sub-functions (see 2. MATLAB FUNCTION in Figure 3-3) which allow the tool to carry out a series of calculations to estimate the values of all criteria listed in Table 3-1 for each WSO (see files in the 'Base_model_Matlab_code' zip folder containing all the underlying code and script reports for all Matlab functions).

Figure 3-11 illustrates how the different user input data are fed into each specific Matlab sub-function and how different process outputs are exchanged between Matlab sub-functions to compute all quantitative TBL impacts listed in Table 3-1**.** Care is taken at every calculation step to use the most superior information available and to avoid double-counting, particularly with regards to carbon emissions where input datasets are diverse because of the complexity of accounting for carbon emissions by all processes and throughout the supply chain. The sub-functions are flexible in terms of their underlying datasets and, in the future, could be easily updated to accommodate more recent data.

Table 3-1. Quantitative Criteria Calculated Using the Matlab Function.

Category	Criterion	Units
Economic criteria – WSO Cost and Production	Lifecycle and unit cost	\$, \$/MGD
Economic criteria – Resident income	Resident income	\$
Economic criteria – WSO Cost and Production	Variable cost percentage	%
Economic criteria – WSO Cost and Production	Cost of imported inputs	%
Environmental criteria –Footprints	Carbon footprint	kg CO2-e
Environmental criteria –Footprints	Water footprint	M3
Environmental criteria – Ecosystems	Eutrophication potential	Kg N-e
Environmental criteria – Ecosystems	Ecotoxicity potential	Kg DCB-e
Social criteria – Jobs and Human Health	National jobs created	# of jobs
Social criteria – Jobs and Human Health	Effect on human health	HTP



*1. Sitework, 2. Equipment, 3. Concrete, 4. Steel, 5. Labour, 6. Pipes/valves (general), 7. Instrumentation, 8. Housing, 9. Yard piping, 10. Landscaping, 11. Site electrical, 12. Engineering & legal, 13. PVC pipes, 14. Ductile iron pipes

**1. Electricity (kWh), 2. Natural gas (cubic feet), 3. Diesel (gallons), 4. Labour, 5. Maintenance, 6. Chemicals (organic, inorganic, chlorine, carbon)

Figure 3-10. Detailed Workflow of '2. Matlab Function' Showing How Users Feed Into Each Matlab Sub-Function and How Data is Exchanged to Compute the TBL impacts.

The following sub-sections describe each sub-function. All additional input datasets and sources (such as academic literature, industry reports, or textbooks) are discussed in detail following the order *a* through *e* which corresponds to the same lettering used in Figure 3-11.

3.5.3 2a. Unit Process Cost Breakdown

3.5.3.1 Default Unit Process Costs Curves and Unit Cost Estimates

Calculating detailed costs associated with each WSO is the starting point for each EE-MRIO calculation. The main core of the quantitative model is based on environmentally extended multi-regional input output (EE-MRIO) analysis which includes the complete flow of goods and services that comprise the product supply chains in the Australian, US, and global economies. These data are used to quantify and apportion TBL impacts. The principal input variables to WaterSET are the estimates of all capital and operational expenditures for a given WSO.

Based on the user's selection and sizing of individual unit processes, a dedicated sub-function determines the total Capital, Operations, and Maintenance costs breakdown for each WSO based on multiple default cost curves for each of the selected unit processes. Data reliability of all likely capital expenditure (CAPEX) and operation and maintenance expenditure (OPEX) is a priority in this framework. For the current model setup, the project team has sourced or calculated default cost curves for 74 conventional and advanced treatment unit processes from reliable sources (Kawamura and McGivney 2008; Sharma et al. 2013; Plumlee et al. 2014) which allow the user to 'mix and match' in order to create a water supply option that most closely resembles their desired configuration.

To determine the total CAPEX and OPEX costs and breakdown associated with each WSO, a generalised formula was created that can facilitate cubic, quadratic, logarithmic, power and linear cost functions[11]. This reflects the diversity of cost curve functions available for each of the 74 different unit processes.

Total CAPEX cost for each user-specified WSO is given by:

$$CAPEX_i = \sum_{j=1}^{n} \sum_{R=1}^{14} R_j . N_{ij} \left(a_j {x^3}_{ij} + b_j {x^2}_{ij} + c_j {x^{d_j}}_{ij} + f_j \ln(x_{ij}) + g_{ij} \right) \quad \textbf{(Equation 1)}$$

Similarly, the total OPEX cost is given by:

$$OPEX_i = \sum_{j=1}^{n} \sum_{R=1}^{6} R_j . N_{ij} \left(h_j {x^3}_{ij} + \mathrm{k_j} {x^2}_{ij} + l_j {x^{m_j}}_{ij} + o_j \ln(x_{ij}) + p_{ij} \right) \quad \textbf{(Equation 2)}$$

where *i* is the WSO, *j* is the unit process (*n*=74),*x* is the unit process size (the units vary with each unit process, for example many filtration processes are often in square feet whereas chemical feed is in pounds per day), *R* is the cost breakdown ratio for each unit process (there are 14 breakdown categories for CAPEX and 6 for OPEX, as shown in Figure 3-11), and N is the number of unit processes of each type (e.g., two gravity filters of a certain size *x*). *a*, *b*, *c*, *d*, *f*, *g*, *h*, *k*, *l*, *m, o, p* are all constant factors which depend on the CAPEX and OPEX cost curve of each individual unit process[12].

While the cost curves used by WaterSET represent the value of the U.S. dollar (or Australian dollar) during a specific year which varies from one cost curve to another, WaterSET converts the CAPEX and OPEX to nominal values using the Engineering News Record (ENR) overall index and the ENR and Bureau of Labor Statistics (BLS) indices specific to an input. The user instructs WaterSET as to which year will be represented by the lifecycle costs and U.S. income impact by entering the index values in the input section of the model.

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[11] This could be extended for higher order polynomials if necessary.

[12] Please note that many of the constant factors are equal to zero at every iteration since any given unit process will be assigned to one type of cost function.

The disaggregation of CAPEX and OPEX into constituent categories (using the vector *R*), is a significant part of the cost calculation procedure because in an EE-MRIO model each unit process is associated with a different input recipe and therefore a different total impact multiplier. This means that the same amount of total expenditure for a WSO may still have completely different TBL impacts depending on which sectors of the economy are providing the WSO inputs. Since the construction of each unit process entails a different mix of inputs depending on its specific characteristics[13], data from the literature was used to assign input ratios (*R*) to each individual unit process (Kawamura and McGivney 2008; Sharma et al. 2013; Plumlee et al. 2014). The cost breakdown ratios (R) used for each treatment train and its attributed source are available in the CAPEX and OPEX cost curve spreadsheets in the 'Final_report_supplementary_spreadsheets' zip folder.

Once costs have been estimated and disaggregated for the WSO using Equations 1 and 2, the allocation of itemized CAPEX and OPEX costs to the appropriate NAICS industry sectors in the EE-MRIO table is provided in 'CAPEX_sector_concordance_AUS_US.xlsx' and 'OPEX_sector_concordance_AUS_US.xlsx' of the 'Final_report_supplementary_spreadsheets' zip folder. There are different concordances for the U.S. and for Australia and the itemized costs need to match the official industry classification of each country as used in the underlying EE-MRIO table used to perform the calculations.

In addition to individual unit processes, the CAPEX and OPEX cost functions also include full-blown plants as specified in Kawamura and McGivney (2008). While Kawamura and McGivney (2008) provide cost curves that estimate total CAPEX, the itemized CAPEX and OPEX had to be computed *a priori*, based on the procedure described in Equations 1 and 2, by assuming that each itemized expenditure is equal to the weighted average of all individual CAPEX and OPEX unit process cost itemizations included in each type of plant. This calculation is based on the supplementary data in Kawamura and McGivney (2008) [14]. In addition to the conventional full-blown plants, five different desalination plants are provided as possible options (see CAPEX and OPEX cost curves in 'Final_report_supplementary_spreadsheets' zip folder). Data for these were obtained from a combination of sources but primarily reflect desalination plants in California (Sommariva 2010; Cooley and Ajami 2012; WRDC 2012).

To allow comparisons between WSOs of different capacities, the unit cost concept, defined as the total cost ($) per unit of water supplied forms the basis for the CAPEX and OPEX calculations (Cooley and Ajami 2012; Zhou et al. 2014; Shahabi et al. 2015). This allows scaling CAPEX and OPEX depending on the capacity and flow rate of the proposed WSO and the appropriate input recipe (either default or user selected). Total unit cost including the breakdowns for CAPEX and OPEX are calculated as follows:

$$Unit\ cost_{ki}\ (\$/kgal\,) = \sum_{k=1}^{n} \frac{(annualized\ CAPEX_{ki} + annual\ OPEX_{ki})}{annual\ water\ yield_i\ (kgal)} \qquad \textbf{(Equation 3)}$$

where *i* is the WSO, *k* is one of the CAPEX/OPEX categories (*n*=20) and 1 kgal is the functional unit[15] of the analysis (in the Australian version of the tool the functional unit is 1 m^3). At this stage, the unit cost breakdown needs to be supplemented with cost estimates from the other sub-functions (see Figure 3-11) before it can be used to calculate the total life cycle cost (LCC) which requires all

[13] For example, some processes are more labour-intensive than others while the type of structures and instrumentation required can also vary considerably between different unit processes.

[14] These have been calculated as the weighted average of the multiple individual unit processes contained in different plants for a range of capacities (typically between 10-100 MGD).

[15] The functional unit, 1 m^3 of produced water in many water-related LCA studies, is used to define the primary purpose of a system and to enable comparisons between functionally equivalent WSOs (Zhou et al. 2014).

additional costs from fuels and electricity to be added, along with a consideration of annual interest rate and plant service life entered by the user in the initial inputs screen.

3.5.3.2 Chemical Costs

Chemical quantities and costs are not included in the default cost curves in order to avoid generalised assumptions about chemical needs and dosages. Instead, the user enters the chemical types and dosages to reflect local source characteristics and water quality requirements (as shown in Figure 3-5). The tool includes chemical prices determined through a market survey (as shown in Figure 3-10). However, the user can modify these costs in the 'Indices+Universal Variables' tab of the tool spreadsheet. Each chemical is assigned to an appropriate IO sector. The U.S. NAIC classification distinguishes between organic, inorganic, chlorine and black carbon chemicals. Similarly, to all other background cost spreadsheets, it is envisaged that an expert user could update this underlying table with chemical costs to reflect future prices and local/seasonal chemical price fluctuations.

3.5.3.3 Converting Cost Breakdown to IO Sector Inputs

Disaggregated unit costs must eventually be assigned to specific input-output (IO) industry sectors (this is necessary in order to pass to step 2e). The matching is performed by constructing concordance matrices between each CAPEX and OPEX category on the one hand, and one or more IO industry sectors on the other. The choice of IO sector depends on the nature of each input category. The project team consulted utility cost engineers at Hazen and Sawyer to assist in building the concordance matrices. An example is provided in Table 3-1 and CAPEX and OPEX full concordances are provided in the 'Final_report_supplementary_spreadsheets' zip folder. Despite the project team's best efforts, the task of matching CAPEX and OPEX input categories to IO industry sectors is imperfect because IO sectors tend to be broad aggregates of multiple smaller industries (Miller and Blair 2009; Lenzen 2011; Marin et al. 2012; Pairotti et al. 2014). Nevertheless, the breakdown is still sufficient to reflect the diverse economic and environmental intensities of each cost sub-category.

While the current list of 74 unit processes or full-blown water treatment plants is by no means exhaustive, the list is large enough to allow for many possible WSO configurations (including advanced treatment plants such as those associated with IPR and DPR) and provides a good basis for meaningful comparisons of options available to water utilities. Expert users could theoretically modify the underlying cost curves in future releases of WaterSET, but this will necessitate a degree of training and familiarity with the underlying Matlab code (supplied as supplementary electronic material). In a similar way, the user could also modify the concordance matrix between CAPEX/OPEX categories and IO sectors. The framework developed in this project is thus flexible and allows for regular updating and further refinement.

Table 3-2. Sample of CAPEX-NAICS Concordance Table Used in the Model to Assign Costs to NAICS IO Sectors.

CAPEX Category	U.S. NAICS Sector 1
EXCAVATION & SITEWORK	Other non-residential structures
EQUIPMENT	Other commercial service industry machinery manufacturing
CONCRETE	Ready-mix concrete manufacturing
STEEL	Steel product manufacturing from purchased steel
PIPES & VALVES	Plastics pipe and pipe fitting manufacturing
ELECTRICAL EQUIPMENT	Industrial process variable instruments manufacturing
HOUSING	Non-residential commercial and health care structures
YARD PIPING	Plastics pipe and pipe fitting manufacturing
SITEWORK LANDSCAPING	Greenhouse, nursery, and floriculture production
SITE ELECTRICAL & CONTROLS	Non-residential commercial and health care structures
ENGINEERING	Architectural, engineering, and related services
PVC	Plastics pipe and pipe fitting manufacturing
DUCTILE IRON	Fabricated pipe and pipe fitting manufacturing
OPEX CATEGORY	**US NAICS SECTOR 1**
ELECTRICITY	Electric power generation, transmission, and distribution
NATURAL_GAS	Natural gas distribution
DIESEL	All other petroleum and coal products manufacturing
MAINTENANCE	Non-residential maintenance and repair
INORGANIC_CHEMICALS	All other basic inorganic chemical manufacturing
CHLORINE	Alkalies and chlorine manufacturing
ORGANIC	Other basic organic chemical manufacturing
BLACK_CARBON	Carbon black manufacturing
KEROSENE	All other petroleum and coal products manufacturing

3.5.4 2b. Fuel Costs and GHG Emissions

This sub-function uses all the information the user enters in the fuel- and residuals- related input cells to calculate the costs and direct (scope 1) GHG emissions from the burning of fuels on-site and during the transportation of residuals from the plant to the disposal site. The residuals disposal calculation is a simple consideration of the total vehicle distance from the plant to the disposal site and depends on user inputs (this is given by the number of truckloads times the distance per day) translated into carbon emissions and costs. The user also has the option to enter any additional disposal costs that may be incurred. The function also receives the estimated natural gas and diesel portion of the OPEX that is calculated as a physical quantity from the unit process cost curves in 2a (see Figure 3-11).

The sub-function performs simple linear calculations based on the latest fuel prices and GHG factors and returns estimates of scope 1 GHG emissions in addition to cost estimates for different fuel types. Prices and GHG emissions factors for different fuels are sourced from the U.S. Energy Information Administration (EIA 2016). The tool includes the latest prices, but the user is encouraged to modify these prices in 'Indices+Universal Variables' in order to ensure they reflect current costs.

3.5.5 2c. Conveyance Costs and Energy

This sub-function performs calculations to determine the costs, energy, and other TBL impacts related to the construction and operation of pumping stations and associated piping installations. Water pumping is often a significant contributor to energy use for certain WSOs and can therefore be a significant differentiating factor when it comes to screening and selecting between options. These additional conveyance calculations (available for water and reclaimed water transmission systems) allow a more comprehensive picture of energy requirements, environmental impacts and costs.

The conveyance sub-function uses a simple hydraulic pump power calculation[16] which proceeds on the basis of user inputs (see Figure 3-6 and Figure 3-7) by considering the total head loss of the system, using the following equation:

$$P_{h(kW)} = q\ \rho\ g\ h\ /\ (3.6 \times 10^6) \qquad \textbf{(Equation 4)}$$

where $P_h(kW)$ = hydraulic power (kW), q = flow capacity (m3/h), ρ = density of fluid (kg/m3), g = gravity (9.81 m/s2), h = differential head (m). Shaft pump power is finally estimated by dividing $P_h(kW)$ by the pump efficiency.

Costs associated with pump station construction and operation are calculated on the basis of cost curves from the literature (Jones et al. 2008) (see Figure 3-6 and Figure 3-7). Once the total power required per day is calculated it is added to the total electricity demand (see 2d in Figure 3-3and Figure 3-11). Cost curves for pumps and boosters (assumed where the total head is greater than 300 ft) are also sourced from Jones et al. (2008).

3.5.6 2d. Electricity GHG Emissions (eGRID Profiler)

Depending on the user's choice of unit processes and inputs (and their respective energy requirements), the location of the utility (as indicated by the state and postcode), and any onsite energy or electricity production as entered by the user, the model uses the 2015 edition of the U.S. Environmental Protection Agency's Emissions & Generation Resource Integrated Database (eGRID[17]) scope 2 and 3 electricity emission factors to estimate the total greenhouse gas emissions associated with the annual OPEX of each WSO (see Figure 3-11). The map of the eGRId sub-regions is provided in Figure 3-12.

The sub-function selects the appropriate sub-region on the basis of the postcode by using the tables provided in the eGRID Power Profiler Emissions Tool (EPA 2015). The corresponding CO_2, CH_4 and N_2O factors are used to estimate carbon emissions in CO_2-e (see power profiler tool in 'Final_report_supplementary_spreadsheets' zip folder).

GHG estimates from electricity (scope 2) are added to scope 1 (from direct on-site fuel use provided by the MATLAB sub-function 2b in Figure 3-3) and scope 3 (from purchased inputs related to the CAPEX and OPEX breakdown provided by the MATLAB sub-function 2e in Figure 3-3) to give a full supply chain figure for GHG emissions associated with each WSO.

[16] see for example http://www.engineeringtoolbox.com/pumps-power-d_505.html
[17] https://www.epa.gov/energy/egrid

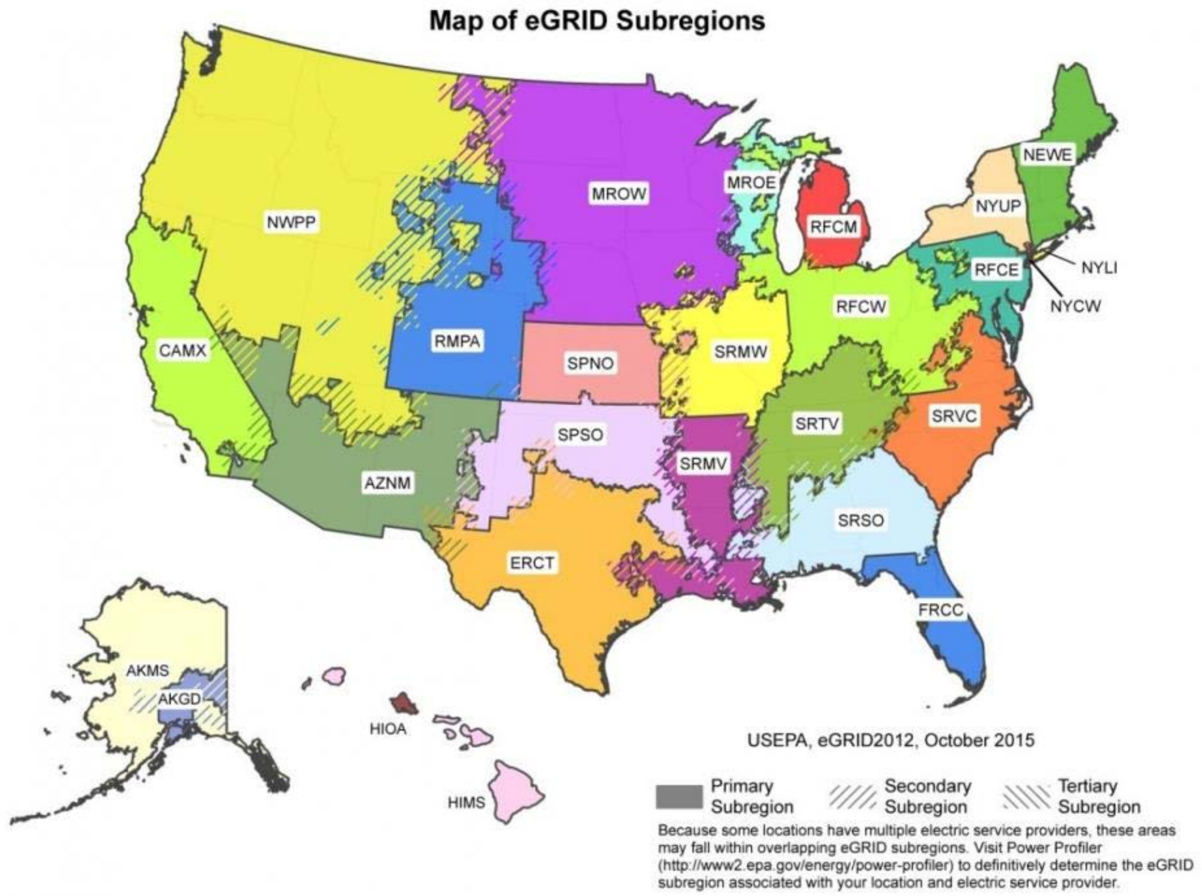


Figure 3-11. Map of eGRID Subregions, with Each Subregion Having Its Own Carbon Emissions Factors that Reflect the Local Electricity Mix.
(Source: EPA 2015)

3.5.7 2e. Hybrid EE-MRIO LCA and LCC Model

3.5.7.1 Computing TBL Impacts

Once all total costs and the cost breakdown have been calculated for OPEX and CAPEX, this final major sub-function creates a new sector of the economy that corresponds to the 'new' WSO and assigns these costs to the appropriate IO sectors (using the concordance matrices described earlier in step 2a). Finally, it computes all quantitative TBL impacts associated with each WSO using the EE-MRIO model. To better understand this procedure, it is necessary to explain how the EE-MRIO model works and how it compares to alternative life cycle methodologies. Following a brief discussion on the merits of the chosen method, this section elaborates on the customization of the method for the purposes of this project.

3.5.7.2 EE-MRIO LCA – Theoretical Background

EE-MRIO is an IO-based hybrid Triple Bottom Line-LCA that combines the merits of top-down input-output accounting and detailed process-based LCA, in what is considered by most experts to be a 'best of both worlds', state of the art approach (Suh and Nakamura 2007; Rowley et al. 2009; Wiedmann et al. 2009). This section briefly introduces input-output analysis (IOA) and process-based LCA, focusing on their respective data inputs, merits and limitations. It concludes by elaborating how the proposed method can deliver a comprehensive TBL water supply assessment tool.

IOA is based on the input-output (IO) accounting framework, developed by Wassily Leontief at Harvard University in the late 1930s, and for which Leontief was later awarded the Nobel Prize in Economic Sciences in 1973. IOA makes use of monetary flows between economic sectors in order to account for complex interdependencies between industries, such as relating the use of membranes in water treatment to the starting materials in crude oil products. Information on monetary flows in the economy is typically available in the form of input-output tables (IOTs), which are essentially large matrices that describe economic flows between sectors in the economy (including all sale and purchase relationships between producers and consumers) (Eurostat 2008; OECD 2015). Many countries, including Australia and the United States, publish IOTs on a regular basis (Onat et al. 2014). Based on these IOTs it is possible to employ matrix algebra[18] to capture the infinite supply chain. Multi-regional input-output tables (MRIOTs), such as the ones used in this study, are IOTs that also include trade and economic interdependencies across countries (see Section 3.5.7.3).

An extension of the basic economic IO model, pioneered by Leontief himself in the early 1970s, allows adding any kind of economic, environmental, and social coefficient for which data are available to the IO structure. Thus, with the use of IOTs and appropriate coefficients, it is possible to estimate the full supply chain economic costs and benefits (such as value added contribution), 'environmental footprints' (for instance, water, land, energy and carbon), and social costs and benefits (e.g., employment, income, and government revenue) of any kind of project or investment (Wiedmann et al. 2009; Onat et al. 2014). This kind of extended IO model has already been successfully employed in a number of academic and non-academic multi-indicator TBL assessments (Lenzen 2003; Foran et al. 2005; Wiedmann and Lenzen 2008; Wiedmann et al. 2009; Onat et al. 2014).

The extended IO model can be expressed mathematically as follows:

$$E_i = F(I - A)^{-1} y_i \quad \textbf{(Equation 5)}$$

where E_i = total impact of each WSO (in this case E is a vector with 10 elements corresponding to the quantitative criteria in Table 3-1), F = matrix of direct sectoral intensities for each criterion, A = input-output coefficient matrix (containing the sector input recipes required to generate each dollar of output in the economy), and y = vector of final demand (in this case the sale of water produced by the WSO to consumers assuming unit cost pricing).

The IO model can be tailored to the context of sustainable water management, as mentioned in a recent report by the ATSE (ATSE 2012). In order to make this generic framework explicit to different water treatment and supply options, specific process data (e.g., energy inputs, chemicals, pumping and onsite fuels) have also been incorporated. Process-based LCA, or simply process analysis, accounts for all resource use and environmental releases from on-site production as well as those up to a certain point in the upstream supply chain (Suh et al. 2004a). The advantage of process analysis is its detail and specificity to the actual physical processes involved with operation and supply chains. In this project, process analysis allows the direct use of water utility costs and required inputs for different WSOs.

The reason for using a hybrid approach rather than just process data on their own, is to avoid the well-known truncation error. For example, process analysis may often only account for direct impacts and first-order supply chain impacts (this could be the retailers from which a water utility purchases its inputs), thereby leaving out additional supply chain considerations. As it is impossible to gather process data for the entire supply chain, all higher upstream impacts are calculated by using the IOA framework.

The practical implementation of IO-based hybrid TBL-LCA proceeds via the disaggregation of water supply inputs and costs to be compatible with the IO framework and the insertion of process-specific utility data for different technologies This method has a sound theoretical basis (Joshi 1999; Suh 2004). Recent manifestations of this approach include applications to renewable energy technologies (Wiedmann et al. 2011a), biofuels (Malik et al. 2014), and water treatment and supply (Rowley et al. 2009; Alvarez-Gaitan et al. 2013). While the aforementioned studies focused on environmental impacts, the IO-based hybrid TBL-LCA in this case also seamlessly incorporates social

[18] In IO formulation this is known as the 'Leontief Inverse' matrix – this corresponds to $(I - A)^{-1}$ in the equation shown above.

and economic impacts, resulting in a fully comprehensive integrated TBL assessment (Foran et al. 2005; Wiedmann et al. 2009; Onat et al. 2014).

The hybrid TBL-LCA model is thus capable of concurrently quantifying all the TBL criteria considered in WaterSET across the entire supply chain of each water supply option on the basis of cost breakdown estimates obtained in "2a Unit Process Cost Breakdown".

3.5.7.3 Customized EE-MRIO LCA Model

TBL impacts are estimated using a customized environmentally extended multi-regional input-output (EE-MRIO) table extracted from the Eora global MRIO tables (Lenzen et al. 2012; Lenzen et al. 2013). In this table called "MRIOT", the U.S., Australian and Chinese economies are disaggregated and represented by their own country matrices called "Inter-Industry Transactions Table" (see diagonal in Figure 3-13). The MRIOT also contains a "Rest of the World" transactions table to allow a complete simulation of global trade flows. All input data in the EE-MRIO model represents the year 2012 and the model outputs are converted to the year specified by the user.

Each row and column in the table is one of the industries that comprise the economy. For example, 429 industries comprise the U.S. economy as depicted in its Inter-Industry Transactions table in Figure 3-13. Each row of the table describes how much of the industry's output in dollars is distributed to each of the other industries and to itself. Each column of the table describes how much of the output in dollars from other industries and from itself is used to produce that industry's output.

The procedure follows input-output based hybrid life cycle assessment where direct input costs (such as CAPEX and OPEX cost breakdowns) are inserted into the input-output table to create a new sector representative of a new technology (Suh et al. 2004b; Suh and Huppes 2005; Wiedmann et al. 2011b; Malik et al. 2014; Wolfram et al. 2016).

Following creation and insertion of a new sector corresponding to the WSO (as shown in Figure 3-13), EE-MRIO multipliers are calculated using the conventional Leontief model. A simple illustration of this procedure is shown in Figure 3-13. This is the most computationally intensive sub-function as it involves large matrix inversions to determine the full supply chain multipliers for each criterion. The code and equations are not visible to the tool user but are made available in the form of the underlying Matlab scripts (see Supplementary Datasets). Please refer back to Section 3.5.7.2 or to Miller and Blair (2009b) for more details on the mathematics of IO.

These multipliers are used to estimate TBL impacts for all quantitative criteria. The exception is lifecycle cost which is calculated separately based on the cost curve estimates (see Section 3.5.3.1) in addition to the other costs for inputs such as chemicals and onsite fuels specified by the user. The economic and environmental criteria values are based on data from the Eora database[19] and the criteria values for eutrophication, ecotoxicity, and human toxicity are based on data from the Comprehensive Environmental Data Archive (CEDA)[20] (Suh 2009).

Each quantitative criterion is represented as a vector of values of direct intensity of each sector in the economy. The full set of direct intensity vectors together makes up the F matrix (see Equation 5) above and Figure 3-13). The cost estimates are inserted as a column into the inter-industry transactions table of the EE-MRIO table. The standard Leontief calculation (this corresponds to $F(I-A)^{-1}$ in Equation 5) is then carried out to calculate total intensity multipliers and captures impacts along the entire supply chain for the newly created WSO sector. The same procedure is repeated for each WSO configuration being evaluated, with each combination of inputs yielding different intensity multipliers that are used to estimate the total impact of each WSO across all quantitative criteria.

[19] http://worldmrio.com
[20] http://cedainformation.net

	WSO	Criteria			
		Indicator 1	Indicator 2	...	Indicator *n*
Options	DPR	y_{11}	y_{12}	...	y_{1n}
	Desalination	y_{21}	y_{22}	...	y_{2n}
	...	...	...	...	...
	WSO m	y_{m1}	y_{m2}	...	y_{mn}

- A set of n criteria C = { c_1 , , ... c_n } (e.g. carbon footprint; eutrophication potential etc.)
- A set of m alternatives X = { a_1 , , ... 1_m } (in this case different WSOs)
- An m by n evaluation matrix E (also called a 'performance table') containing the evaluation of each alternative on each criterion.

Figure 3-12. Depiction of the Hybrid IO-Based LCA Method Showing an Example of How Disaggregated CAPEX and OPEX Costs Have Been Used to Create a New Water Supply Sector in the U.S. Economy by Inputting Model-Estimated Values for Chemicals, Electricity, and Concrete.
(AUS = Australia, USA = United States, CHN = China, RoW = rest of world)

3.5.7.4 LCC Calculation

The life cycle cost (LCC) estimate is the present value of the capital cost (CAPEX) and operating cost (OPEX) over the life of the WSO divided by the total WSO capacity as provided in Equation 6. The CAPEX and OPEX are estimated using Equations (1) and (2) provided in Section 3.5.3.1.

$$LCC = \frac{CAPEX + \sum_{i=1}^{n} OPEX_i (1+r)^{-i}}{W * 1000 * 365 * n}$$ **(Equation 6)**

where *LCC* = lifecycle cost per kgal in NPV, *r* = real (no inflation) interest rate, *W* = daily flow rate in MGD, and n= plant service life. During the calculation in Equation 6, CAPEX and OPEX are in 2012 dollars. This will generate an LCC in 2012 dollars which is then converted to the year represented by the cost indices provided by the user.

As shown in Figure 3-8, in WaterSET, users have the option to either allow the tool to calculate LCC based on default cost curves or enter their own costs for a specific year. In the former case, the CAPEX and OPEX calculations are carried out as per Equations 1 and 2, followed by Equation 6. In the latter case, where the user enters their own CAPEX and OPEX costs, only Equation 6 is necessary with the costs converted to current costs using the ENR CCI index.

The costs used to compare WSOs should be estimated in a consistent manner among all of the WSOs. For example, if the cost of WSO 1 is estimated through user-selected unit processes, then the cost of all WSOs that are being compared to WSO 1 should be estimated through user-selected unit processes. Another example is the use of cost estimates provided by the user. If the user provides their own WSO cost estimates, then the user should provide estimated costs for all the WSOs being compared such that the costs are estimated in a consistent manner.

3.5.8 3. Criteria Table

The criteria values are compiled into a performance table depicted in Figure 3-14 that contains the raw values of all TBL criteria selected by the user, including all economic, environmental and social criteria. In the tool this corresponds to the 'Criteria Matrix' tab, where all criteria for each of the WSOs are brought together in one table as depicted in Figure 3-15. At this stage, the numbers are the raw values prior to performing the MCDA. The user may plot the 10 unweighted quantitative criteria in a radar plot by clicking on 'Generate Radar Chart'. For a more holistic TBL assessment, the user may choose to conduct an MCDA by clicking on "Run MCDA".

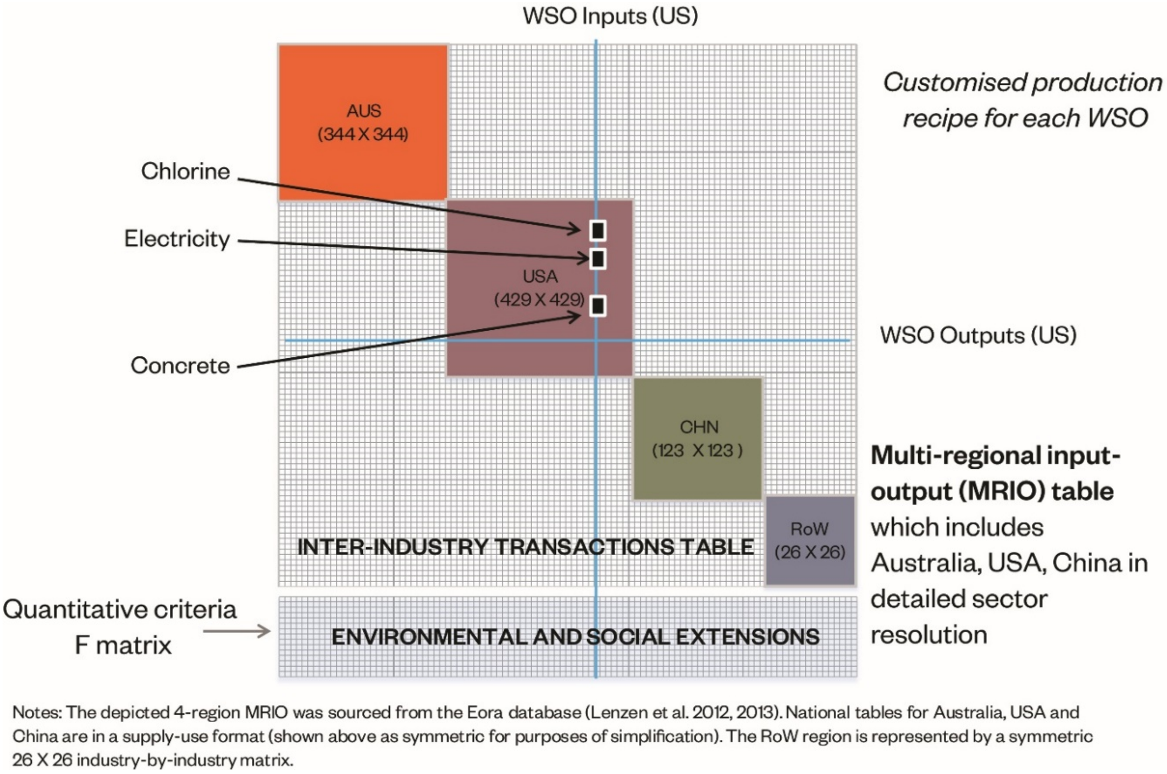


Figure 3-13. Performance Table Listing Criteria Values for Each WSO.

Before invoking the MCDA function, direct user input is required to fill in the values for the social criteria as listed in Table 3-3 and to select the appropriate weights. A zero value is possible if the user does not consider the criterion to be of significance. A pie chart at the bottom of the 'Criteria Matrix' tab allows the user to visualize that their selected mix of weights has their desired balance between economic, environmental and social criteria. The user may also enter additional criteria by clicking the 'Add Criteria' button which prompts the user for the name and type (quantitative or qualitative; positive or negative) of criterion to be added. The tool is designed so that the user may enter up to two additional criteria.

Table 3-3. Social Criteria Values Included in the Performance Table.

Category	Criterion	Units
Social criteria – Risk and public acceptance	Drought Resilience	0 to 4 points
Social criteria – Risk and public acceptance	Public Acceptance	$ or hours
Social criteria – Risk and public acceptance	Further Social Benefits	0 to 11 points
Social criteria – Risk and public acceptance	Implementation Risk	0 to 4 points
Social criteria – Jobs and Human Health	Pollution Impacts	1-10 Likert
Social criteria – Jobs and Human Health	Waste Disposal Impacts	1-10 Likert
Social criteria – Jobs and Human Health	Construction Impacts	1-10 Likert
Social criteria – Jobs and Human Health	Operational Impacts	1-10 Likert

A screenshot of the WaterSET performance is provided in Figure 3-15. In this example, WaterSET has calculated and entered the values for the quantitative criteria. The user is expected to fill in the values for the social criteria and select appropriate weights for each criterion.

Criterion (click square buttons below for detailed description)	Description	Unit	Qualitative (L) or Quantitative (T)	Positive or Negative	Weight	Carbon-based groundwater augmentation	Membrane-based groundwater augmentation	Default RO Plant
Lifecycle cost	Lifecycle cost to utility per unit of \	$	T	Neg	10	5.25	5.16	6.59
Amount of water produced	Average annual amount of water p	MGD	T	Pos	8			
Outside capital cost %	Percent of capital cost to be paid b	%	T	Pos	0			
Resident income	U.S. resident income per unit of wa	$	T	Pos	8	3.63	4.01	5.84
Variable cost %	Variable cost percentage to captur	%	T	Pos	10	35.59	48.85	67.96
Cost of imports %	Cost of imported capital and annua	%	T	Neg	10	16.08	14.11	13.11
Carbon footprint	Carbon footprint in tons of Equivale	kg CO2-e	T	Neg	10	16.47	19.82	26.83
Water footprint	Water footprint in units of water re	gallons	T	Neg	8	5,640.38	6,335.97	9,144.19
Eutrophication potential	Eutrophication potential – kg N equ	kg N equivalent	T	Neg	8	0.00	0.00	0.00
Ecotoxicity potential	Ecotoxicity potential – kg DCB equi	kg DCB equivalent	T	Neg	10	1.91	1.62	1.59
Land footprint	Land footprint per unit of water prc	hectares	T	Neg	10			
Impact of residuals	Impact of residuals disposal and/o	$	T	Neg	10			
National jobs created	National jobs created during const	Number of FTE jobs	T	Pos	10	0.10	0.10	0.14
Effect on human health	Effect of potential pollution causec	HTP	T	Neg	10	0.00	0.00	0.00
Drought Resilience	Resilience of the WSO to drought	0 to 4 points	L	Pos	5	1	1	
Potential Public Acceptance	Potential Public Acceptance (Budg	$ or hours	T	Neg	10	24	24	
Further Social Benefits	Other perceived social benefits	0 to 11 points	L	Pos	8	7	7	
Implementation Risk	Risk	0 to 4 points	L	Pos	8	3	2	
WSO Pollution Impacts	Pollution (not considered elsewher	1 to 10 points	L	Neg	10	1	2	
WSO Waste Disposal Impacts	Waste disposal impacts (e.g brine	1 to 10 points	L	Neg	10	1	6	
WSO Construction Impacts	Construction impacts (not consider	1 to 10 points	L	Neg	8	1	2	
WSO Operational Impacts	Operational impacts (not considere	1 to 10 points	L	Neg	10	1	1	

Figure 3-14. Full Criteria Matrix Screenshot from the Tool Showing All Criteria in the MCDA with Pre-Assigned Weights.
Cells in yellow require user inputs, whereas the white cells are pre-populated with model estimated quantitative criteria using the EE MRIO LCA mo

3.5.9 4. MCDA Function (EVAMIX)

WaterSET uses EVAMIX (Maimone 1985a; Maimone and Crockett 2003) as the chosen MCDA algorithm that converts the raw values of the criteria into scores that can be compared among WSOs. The box below provides a qualitative description of the EVAMIX method. For a more detailed quantitative description please refer to Maimone (1985a).

EVAMIX Algorithm Steps

The EVAMIX method is an outranking approach that looks at pairwise comparisons of model outputs. Unlike in the most commonly used MCDA method known as the sum of aggregated weights (SAW), a pairwise comparison is made for all pairs of alternatives (*i*, *i'*) to determine an appraisal score for each. In this way, the EVAMIX algorithm considers the one-to-one performance of a WSO across all criteria and against each alternative WSO.

The approach includes the following main steps: 1) separating qualitative and quantitative criteria; 2) calculating dominance scores for all criteria; 3) calculating standardized dominance scores for all criteria; 4) calculating overall dominance scores; and 5) calculating appraisal scores for each alternative (Voogd 1983). The details of each step are described below:

Step 1: Separating qualitative and quantitative criteria

Within the EVAMIX approach, qualitative and quantitative criteria are treated separately. A two-dimensional matrix with criteria and alternatives is constructed. This matrix is then divided into two sub-matrices, one for qualitative criteria and another for quantitative criteria (Maimone 1985b).

Step 2: Calculating dominance scores for all criteria ($\alpha_{ii'}$ and $a_{ii'}$)

Dominance scores, $\alpha_{ii'}$, for qualitative criteria and, $a_{ii'}$, for quantitative criteria are calculated. These dominance scores represent the degrees to which WSO *i* dominates WSO *i'* (Voogd 1983). Dominance scores are calculated for each possible pair of WSOs for each criterion.

Step 3: Calculating standardized dominance scores for all criteria ($\delta_{ii'}$ and $d_{ii'}$)

As the dominance scores for qualitative and quantitative criteria are calculated to different measurement units, they are standardized into the same unit in this step (Voogd 1983). This makes the two measurements comparable.

Step 4: Calculating overall dominance scores ($m_{ii'}$)

The standardized dominance scores of qualitative and quantitative criteria are then combined by considering the weights assigned for them. This overall dominance score gives the degree to which alternative *i* is better (or worse) than alternative *i'* for a given set of criteria and the weights (Voogd 1983).

Step 5: Calculating appraisal scores for each alternative (s)

The final ranking of alternatives is expressed in the form of the appraisal score, *s*. This dimensionless score represents the worth of a particular alternative relative to the other alternatives (Maimone 1985b).

The simplest form of MCDA, the sum of aggregated weights (SAW), simply normalises and then aggregates all indicators based on user-assigned weights to create a score for each WSO. However, this form of MCDA has been criticised as being overly simplistic and has deficiencies in terms of dealing with semi-quantitative criteria (Rowley et al. 2012). This section provides a justification for the chosen method by outlining its strengths and relevance to the WSO context.

A proliferation of MCDA methods, originating from fundamentally different principles, means that the choice of method can have substantial implications on the final results. However, the ever-increasing number of available options makes it particularly difficult to choose the right method for any specific project (de Montis et al. 2005). Table 3-3 lists each of the requirements used to select EVAMIX as the most suitable MCDA method for WaterSET via the method of elimination**.** The discussion in this section focuses on each of these requirements.

Ability to handle LCA perspective The first requirement was for the chosen method to be able to handle an LCA perspective. This is a feature of most MCDA methods, as they do not generally have any theoretical limit to the number or type of criteria (Cinelli et al. 2014).

Mix of quantitative and qualitative criteria Another crucial requirement was the ability of the MCDA method to evaluation both quantitative and qualitative criteria in a meaningful way (de Montis et al. 2005; Rowley et al. 2012; Cinelli et al. 2014). The presence of both quantitative and qualitative data in the evaluation matrix is often the main source of discrepancy in results from different methods (Hajkowicz and Higgins 2008), thus emphasising the need for a robust method. The EVAMIX is designed so that the information contained in the quantitative and qualitative criteria are accurately used to the maximum extent possible. EVAMIX is an ideal choice in this respect.

Importance coefficients There are two fundamentally different mathematical interpretations of weights in MCDA. Depending on the MCDA method, weights represent either "substitution rates (i.e., they describe the capacity for trade-offs between the criteria) [or] importance coefficients (i.e., they describe the relative importance of criteria)" (de Montis et al. 2005; Rowley et al. 2012, p 31; also Cinelli et al. 2014). Because importance coefficients are more readily derived, and our ability to interact with the decision makers is limited, we have selected an MCDA method that interprets the weights as importance coefficients.

Rank reversal 'Rank reversal' occurs when the addition or removal of an irrelevant (non-preferred) alternative changes the preference order of two or more other alternatives. The preference axiom is: "If you prefer option A when given a choice among A, B, and C, then your choice should not change if C is dropped from the list or if another option, D, is added that is already inferior to one of the other options" (Hubbard 2009, p 138). EVAMIX does not suffer from this issue.

Transparency The various MCDA methods exhibit different degrees of transparency in the decision making process (de Montis et al. 2005). Some methods require such extensive calculations or rely on such complex modelling that they effectively become 'black box' methods, which may reduce decision makers' confidence in the results. EVAMIX is among the methods rated highly for transparency by de Montis et al. (2005).

Ease of use In this project, the desired MCDA method is one that is automated so that users will not need significant assistance from this project's research team. EVAMIX is perfectly suited to automation.

Ability to handle uncertainty Some methods are fundamentally set up to handle uncertain or imperfect information, while others are able to handle uncertainty through the implementation of sensitivity analysis (Cinelli et al. 2014). EVAMIX can handle uncertainty through sensitivity analysis (i.e. varying the input data and re-running the MCDA). EVAMIX also provides for the correct handling of qualitative performance data (i.e. artificial precision is not imposed). It also allows for the 'downgrading' of quantitative evaluations to qualitative evaluations if the uncertainty of the quantitative evaluation is deemed unacceptably high (the latter as described in Maimone 1985a) .

Stakeholder participation Stakeholder participation refers to the ability to engage many decision makers and stakeholders in the evaluation of WSOs. (de Montis et al. 2005). EVAMIX provides the information needed to assess why some WSOs perform better than others.

On the basis of the above criteria, EVAMIX was chosen as the ideal method to handle the multi-criteria aggregation within WaterSET.

Table 3-4. Evaluation of EVAMIX as a Suitable MCDA Method.

Requirements	Yes/No
Ability to handle a life cycle perspective	Yes
Ability to handle mixed quantitative and qualitative data	Yes – this is a defining characteristic of the method
Weights represent importance coefficients	Yes (de Montis et al. 2005)
Rankings are not subject to 'rank reversal'	Yes
Transparency	High (de Montis et al. 2005)
Ease of use	Yes
Ability to handle uncertainty	Yes
Stakeholder participation	Supported (de Montis et al. 2005)

3.5.10 5a. Visualization of Unweighted Results

The user has the option to generate a radar chart which is a visualization of the raw criteria values contained in the performance table. Figure 3-15 is an example of a radar chart where three WSOs are compared across several TBL criteria. WSO 1, the first option, is always treated as the baseline option with other options normalized in comparison to that option. The normalization of indicators is a simple comparison of the value of a WSO's criterion relative to the values of the other WSOs. Higher values on the radar chart indicate a more favorable condition (positive impact) while lower values are less favorable (negative impact).

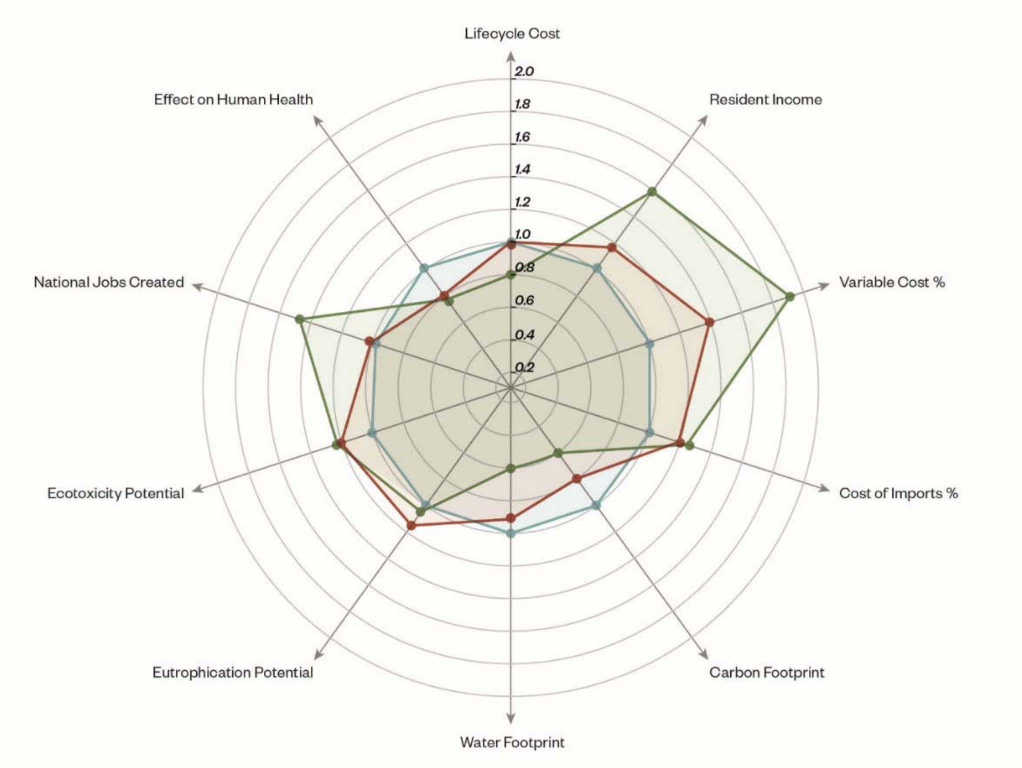


Figure 3-15. Example of a Radar Chart with Raw Criteria Values.

3.5.11 5b. MCDA Results – Overall Weighted WSO Performance

When the user clicks on the button 'Run MCDA', the EVAMIX function is called and the final scores for each WSO are displayed in a chart similar to Figure 3-16. The WSO with the highest score (in this case WSO 3) represents the best option across all criteria given the user-specified weights. The highest score always represents the best option. Numerical scores are relative and do not have any individual significance, as they are unique to each set of weights and values.

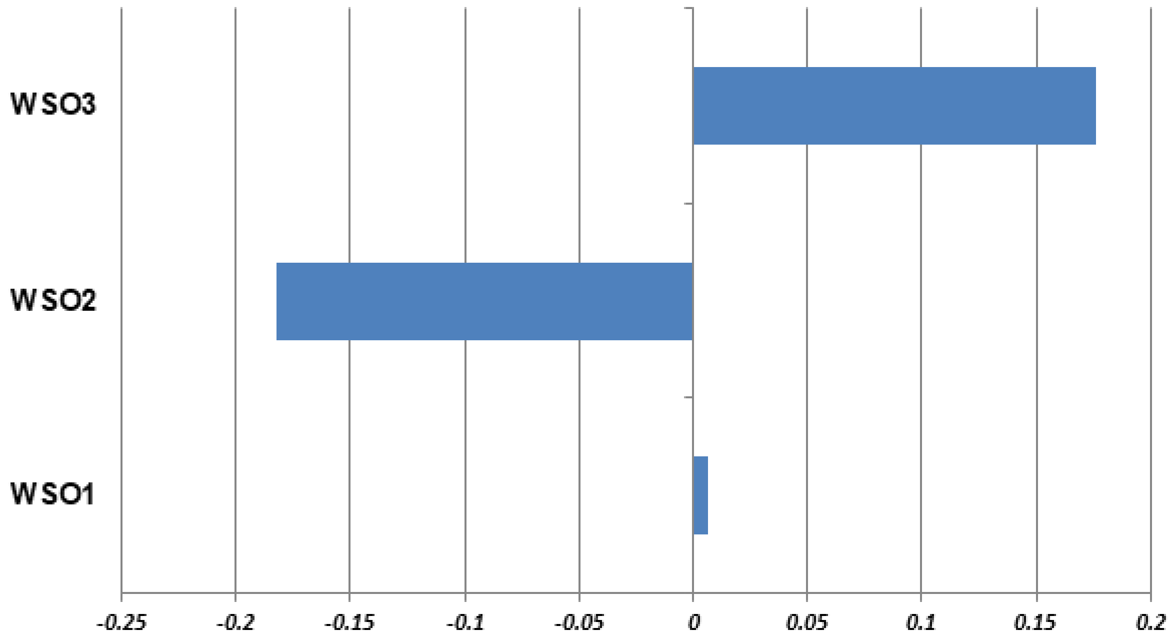


Figure 3-16. Final MCDA Scores Obtained with the EVAMIX Function.

CHAPTER 4

U.S. Case Studies

To evaluate and improve the WaterSET tool's overall user experience and to test its functionality, U.S. case study partners were asked to use the tool to evaluate WSOs. Utility partners were asked to provide as much feedback as possible, including but not limited to any comments on word choice throughout the tool, the feasibility of providing requested information, and interpretation of results. Case study partners included two utilities in the United States and one utility in Australia. A summary of U.S. case study inputs and outputs is provided below; detailed input and output tables for the two U.S. case studies can be found in Appendix D. A discussion of the Australian case study is provided in Appendix E. It is important to note that the Australian evaluation was conducted using the Australian version of WaterSET, the associated files for which can be found in the Australian supplementary file folder. The report speaks directly to the nuances and assumptions that were included in the U.S. version of the tool, although the overall framework is internationally relevant.

4.1 Hampton Roads Sanitation District, Virginia, United States

Hampton Roads Sanitation District (HRSD), a coastal wastewater utility in the Southeastern US, is investigating the implementation of groundwater recharge with advanced treated reclaimed water as an alternative to surface water discharge. This alternative effluent management strategy is being considered due to anticipated regional benefits related to potable water supply, land subsidence, saltwater intrusion, and nutrient management. A key priority of this work was the identification of water quality targets that are protective of human and environmental health, as well as compatible with aquifer chemistry. With these water quality targets in mind, two potential treatment paradigms were tested: 1) carbon-based advanced water treatment, and 2) membrane-based advanced water treatment. The carbon-based option includes coagulation/flocculation/sedimentation, ozonation, biofiltration (BAF), granular activated carbon (GAC), and UV disinfection. The membrane-based option includes ultrafiltration, reverse osmosis, and ultraviolet advanced oxidation process (UVAOP).

In addition to evaluating and comparing these treatment options in terms of finished water quality, the utility aimed to quantify the overall environmental, economic, and social impacts of the treatment processes themselves. Accordingly, the utility used WaterSET to compare the carbon- and membrane-treatment options. This case study highlights that the fact that WaterSET is not only intended for the evaluation of different water supply options, but also for the evaluation of different treatment technologies that may be applied to one given water supply option. Oftentimes, finished water quality targets can be achieved via a variety of treatment technologies, thus suggesting the importance of understanding how technologies compare across various decision making criteria.

Based on previous work and ongoing pilot studies, HRSD input capital and operational requirements for a 1 MGD facility using secondary treated wastewater effluent as raw water, assuming either activated carbon-based advanced water treatment (WSO 1) or membrane-based advanced water treatment (WSO 2). The two water supply options were first compared with a radar chart generated from treatment and conveyance inputs, which shows the relative scores of the two treatment approaches across 10 unweighted quantitative criteria. In all radar charts, WSO 1 is used as the baseline option (i.e., a score of 1.0 for all criteria), with other options normalized in comparison to that option. For all criteria in the radar chart, a higher score is more favorable than a lower score. In Figure 4-1, the results for the two treatment approaches are shown, with the higher (more favorable) scores being split between WSO 1 and WSO 2.

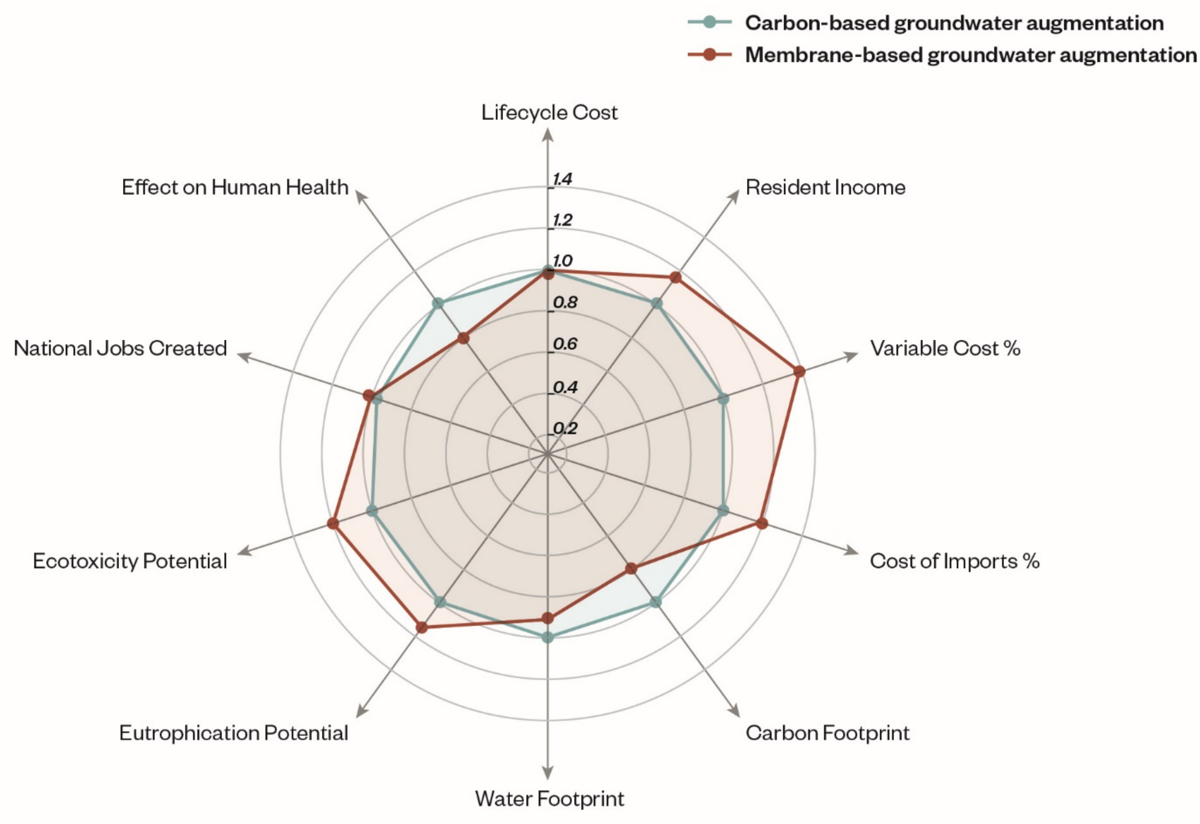


Figure 4-1. Radar Chart Generated from HRSD Inputs Pertaining to Two Treatment Approaches for Groundwater Augmentation.

Overall, the radar chart shows that the most favorable treatment approach varies across criteria. The carbon-based treatment train is shown to be preferred in terms of carbon footprint, water footprint, and effects on human health, whereas the membrane-based treatment train is shown to be preferred in terms of resident income, variable cost percentage, cost of imports percentage, eutrophication potential, and ecotoxicity potential. WSO 1 (carbon-based treatment) and WSO 2 (membrane-based treatment) had comparable scores for the lifecycle cost criterion, which was calculated based on embedded WaterSET cost curves and the HRSD's treatment-related inputs (no cost information from the utility was used in this case). It is important to note is that HRSD's inputs into the WaterSET tool only pertained to treatment and that there were no inputs related to residuals management, thus the lifecycle cost costs for WSOs 1 and 2 may diverge from each other once data related to residuals management is included. Additionally, the results may be different once scaled to larger implementation of 10s to 100s of millions of gallons per day instead of the 1 MGD demonstration cost. Overall, these results highlight the importance of unweighted, disaggregated triple bottom line results, so that one can truly see how the various options compare across individual criteria.

In addition to information related to the carbon- and membrane-based treatment approaches, the utility provided potential criteria weightings to explore how triple bottom line results would be reflected in a multi-criteria decision analysis (MCDA). These criteria weightings were not meant to imply stakeholder input of formal weighting criteria. A high weighting suggests that the specific criterion is important in the decision making process. The MCDA pulls together each water supply option's scores across criteria, as well as weightings for each criterion, to generate one aggregated MCDA score for each water supply option. HRSD weighted six economic criteria, six environmental criteria, and nine social criteria. Figure 4-2 presents a summary of the provided weightings, with each group of criteria being shown with its relative influence on MCDA. More specifically, the following criteria were indicated as the most important (i.e., the highest weighting) in the decision making process: life cycle cost, variable cost percentage, cost of imports, carbon footprint, ecotoxicity potential, land footprint, impact of residuals, national jobs created, effect on human health, public acceptance, pollution impacts, waste disposal impacts, and operational impacts.

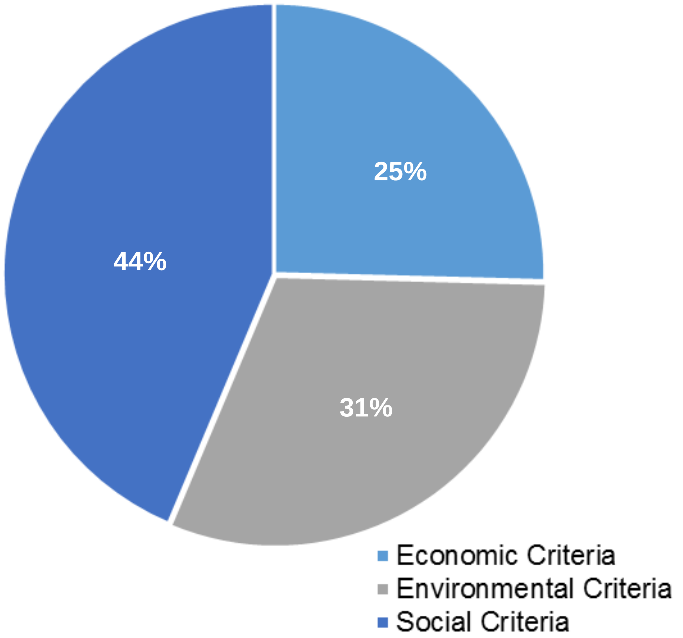


Figure 4-2. Relative Importance of Criteria Categories in the MCD Based on HRSD Inputs Pertaining to Two Treatment Approaches for Groundwater Augmentation.

The results of the HRSD MCDA are presented in Figure 4-3. As previously noted, the MCDA uses the EVAMIX method and the highest score is indicative of the most favorable option, taking treatment process inputs and weightings into account. With regard to the two treatment approaches under consideration by HRSD, the carbon-based treatment option had a higher MCDA score than the membrane-based treatment option, thus indicating its higher level of favorability in terms of the utility's weighting scheme.

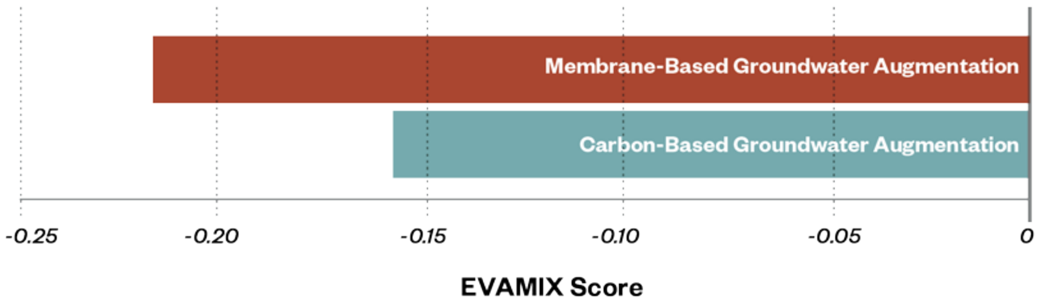


Figure 4-3. MCDA Results for HRSD Inputs Pertaining to Two Treatment Approaches for Groundwater Augmentation and Potential Criteria Weightings.

These results provide the utility with quantitative information about how the two treatment approaches compare across a wide range of decision making criteria. These results, in combination with finished water quality data, help facilitate the utility's decision between the two treatment approaches. WaterSET inputs and associated outputs can be continuously updated as more refined information becomes available as a result on ongoing evaluations.

4.2 Western Utility, United States

A major water district in the Western U.S. is in the early stages of considering various options for increasing their available water supply. Two of the options under consideration include 1) the expansion of an existing recycled water treatment facility to increase the volume of groundwater recharge with advanced treated reclaimed water and 2) the construction of a new seawater desalination facility. The utility had capital and operational information for the option involving increased groundwater recharge; however, the desalination option has not yet been thoroughly investigated. For this case study, the WaterSET tool was used to compare the increased groundwater and charge option (WSO 1) with the new seawater desalination facility (WSO 2). Due to the lesser degree of available project information, WSO 2 used the default reverse osmosis option stored within the tool with the addition of assumed chemical inputs. The WaterSET tool presents results per unit of water produced so that comparisons can be made across water supply options with different capacities.

The radar chart that was generated from the Western utility's inputs is shown in Figure 4-4. As previously discussed, the radar chart is setup such that a higher score is always more favorable, regardless of the criterion. For example, Figure 4-4 shows that WSO 1, increased groundwater recharge, has a higher carbon footprint score than WSO 2, new desalination facility, thus meaning that WSO 1 is more favorable for this criterion (i.e., a smaller carbon footprint). Across all the quantitative criteria in Figure 4-4, the more favorable scores are split between the two water supply options. With respect to criteria such as created resident income, variable cost percentage, the cost percentage of imports, and the creation of national jobs, results show that the new desalination facility is more favorable than increased groundwater augmentation. On the other hand, the increased groundwater recharge option is more favorable for other criteria such as life cycle cost, carbon footprint, water footprint, eutrophication potential, ecotoxicity potential, and effects on human health. Hence overall, the mixed results in the radar chart indicate that one option is not universally favorable across all decision making criteria, thus requiring further evaluation, such as considering the results when criteria are prioritized (i.e., an MCDA with criteria weightings). When comparing these two water supply options, it is important to note that both WSO 1 and WSO 2 do not include inputs related to residuals management, which is expected to be particularly important for both water supply options due to the inputs required for RO brine disposal.

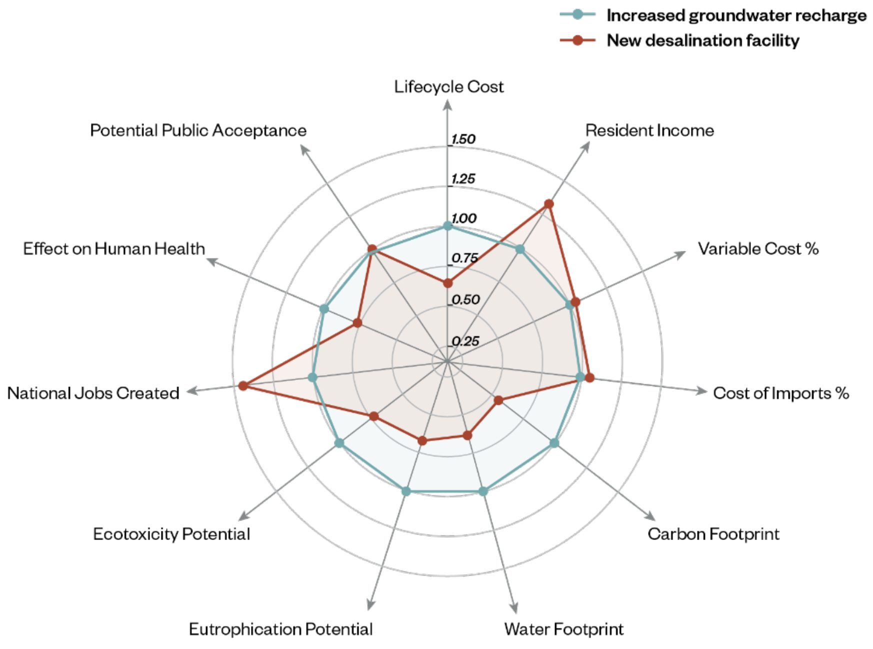


Figure 4-4. Radar Chart Generated from Western Utility Inputs Pertaining to Two Water Supply Options.

In terms of the MCDA, the Western utility did not provide criteria weightings. Instead, two hypothetical MCDAs were run with the Western utility's water supply inputs, one in which there is a high prioritization of economic criteria (Figure 4-5, left) and one in which there is a high prioritization of social criteria (Figure 4-5, right). These two MCDAs were developed and run to evaluate the extent to which the final MCDA output for these specific water supply options would be affected by variation in criteria weightings.

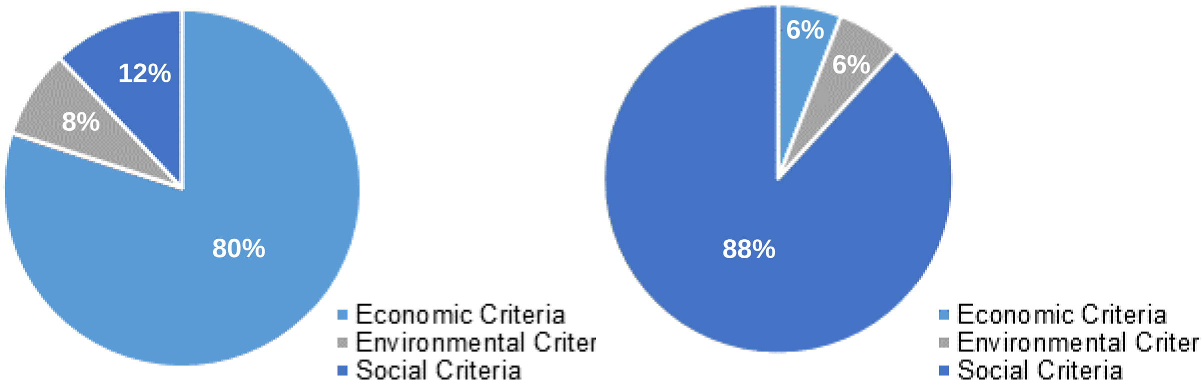


Figure 4-5. Relative Importance of Criteria Categories in the MCDA Based on Hypothetical Western Utility Inputs with an Economic Focus and a Social Focus.

The results of the two hypothetical Western utility MCDAs are presented in Figures 4-6 and 4-7. As previously noted, the MCDA uses the EVAMIX method and the highest score is indicative of the most favorable option, taking treatment process inputs and criteria weightings into account. The MCDA output in Figure 4-6 pertains to the hypothetical criteria weightings with the high prioritization of economic criteria (i.e., economic criteria have the most influence on the total MCDA score). With this weighting scheme, the new desalination facility option had the highest (i.e., most favorable) MCDA EVAMIX score. The MCDA output in Figure 4-7 uses the same water supply inputs provided by the Western utility that are used in Figure 4-6, the one difference being the hypothetical criteria weightings, which now prioritize the social criteria. With this weighting scheme, increased groundwater recharge is the most favorably scored. The new desalination facility becomes unfavorably scored when the social criteria are highly weighted because the desalination facility does not fare well for several of these criteria. For example, included in the social criteria are the following qualitative criteria: pollution impacts, waste disposal impacts, and construction impacts; for these criteria, the Western utility qualitatively scored the new desalination facility less favorably than increased groundwater recharge. It should be noted that the WaterSET tool is set up such that the radar chart presents triple bottom line outputs for quantitative criteria calculated based on WSO inputs, whereas the MCDA calculates an EVAMIX score based on both quantitative and qualitative criteria.

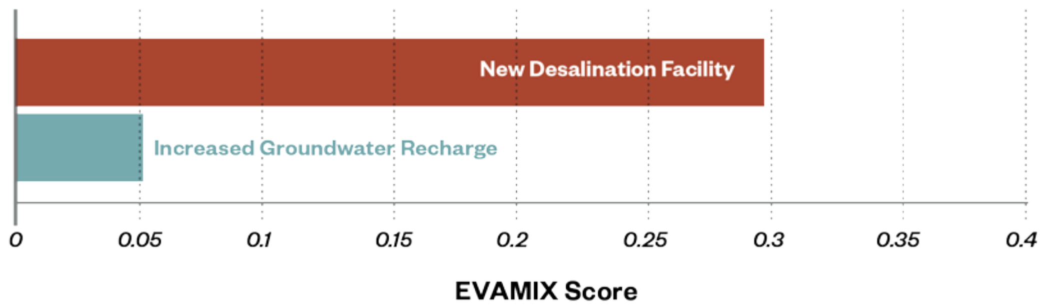


Figure 4-6. MCDA Results for Western Utility Inputs Using Hypothetical Criteria Weightings with an Economic Focus.

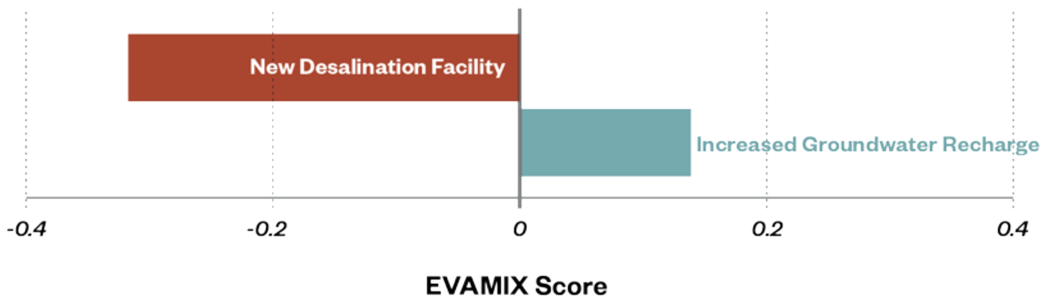


Figure 4-7. MCDA Results for Western Utility Inputs Using Hypothetical Criteria Weightings with a Social Focus.

The different outcomes in Figures 4-6 and 4-7 demonstrate the importance of accurately capturing the decision maker valuation structure via criteria weightings. Prioritization of certain criteria over others can impact how a given water supply option is perceived relative to other options. Additionally, these MCDA outputs highlight why the tool was set up to present the triple bottom line outputs (i.e., the radar chart) separately from the MCDA outputs, as MCDA outputs can vary from user to user based on perceptions of importance (i.e., criteria weightings and inputs for qualitative criteria), whereas triple bottom line outputs are only a function of quantitative WSO inputs.

4.3 Discussion of U.S. Results and Comparisons with Previous Studies

Detailed unweighted model outputs for all quantitative indicators for both case studies are presented in Appendix D. An important issue is that of reliability and uncertainty in calculated values. The high number of indicators and individual numbers also creates a high probability of error. There is a considerable range in TBL impacts across the WSOs which is a product of differences in treatment type and extent, the capacity of each WSO (larger plants benefit from economies of scale), and the amount of fossil fuels versus renewables in the electricity mix (as well differences in the state electricity mix as given by the EPA eGRID data). The major challenge is that values for most of the indicators used cannot be internally validated in the model due to a lack of previous data for the systems under consideration.

It therefore becomes important to benchmark the tool against previous studies in the U.S. and elsewhere that have performed LCA calculations for similar WSOs of treatment configurations. As an alternative means of validation, we conducted a comprehensive comparison of our results against results from the published academic literature for all quantitative indicators shows that the values for all indicators calculated using WaterSET are in the range of those previously reported in the U.S. and elsewhere. Previous study results for all quantitative indicators converted into a common functional unit (m^3) to enable a direct comparison with our outputs from WaterSET. The findings for each indicator can be summarised as follows:

Energy As this is an important indicator with implications for both costs and greenhouse gases (GHGs), a large number of studies have calculated direct energy consumption for water supply systems in the southern U.S. (Stokes and Horvath 2006; Mo et al. 2011; Shrestha et al. 2011; Mo et al. 2014; Stokes et al. 2014; Fang et al. 2015). The average value from these studies is 2.17 kWh/m^3 (SD = 1.51), with values of over 4 kWh/m^3 for some desalination systems. This compares very closely to the values obtained using WaterSET for the 30 MGD SWRO plant in the Southwestern U.S. case study. The results obtained here are also compatible with values of 2.4-8.5 kWh/m^3 reported in international reviews (Gude 2016; Wakeel et al. 2016).

GHG Another commonly reported indicator is GHG emissions. The GHG values obtained in our case study WSOs are higher when compared to previous studies in California (Stokes and Horvath 2006; Stokes and Horvath 2009; Fang et al. 2015) and Nevada (Shrestha et al. 2011) (M = 1.12 kg CO_2-e/m^3, SD = 0.79) and are also on the high end of the 0.4-6.7 kg CO_2-e/m^3 range reported in the international literature (Cornejo et al. 2014). The reason for these higher values is the fact that our hybrid LCA methodology (see Figure 3-11) captures the complete upstream emissions including full scope 3 upstream emissions as opposed to conventional LCA methodologies which tend to be very accurate when it comes to scope 1 and scope 2 emissions but can capture only a small part of the scope 3 emissions (WRI and WBCSD 2004; Rowley et al. 2009; WRI and WBCSD 2011; Fang et al. 2015). An additional reason could be that most of the plants considered in the case studies are small and do not therefore benefit from economies of scale.

Production cost We chose to conduct a comparison of unit production costs (sum of CAPEX and OPEX unit costs, Tables D-3 and D-6 in Appendix D) as opposed to lifecycle costs as this is the value most commonly encountered in the literature. All four WSOs are within the reported range in the U.S. (Shrestha et al. 2011; Cooley and Ajami 2012; Ziolkowska 2015) and internationally (Ghaffour et al. 2013; Gude 2016) for water treatment costs not including conveyance and distribution.

Water footprint Water footprints are also compatible with the 1.05-1.70 m^3/m^3 range reported in recent studies (Renzoni and Germain 2007; Friedrich et al. 2009; Venkatesh and Brattebø 2011; Amores et al. 2013; Lemos et al. 2013; Barjoveanu et al. 2014; Slagstad and Brattebø 2014). It should be noted that the water footprint is representative of the embodied water in the products and processes required to produce the finished product, but not the raw water supply itself, therefore making water footprints less than 1 m^3/m^3 possible.

Eutrophication, ecotoxicity, and human toxicity These indicators are extremely difficult to compare to those in previous studies as they are very often calculated using different inventories and different impact attribution systems. WaterSET uses reliable U.S.-specific environmental extensions for all three indicators (Suh 2009; Bare 2011; IERS 2017). No previous U.S. studies using these environmental extensions were found for comparison, but the order of magnitude was similar to results reported for studies based outside of the U.S. (Rowley et al. 2009; Amores et al. 2013; Lemos et al. 2013). While a comparison against previous study results does not constitute a full model validation exercise, it does provide a means to assess the reliability of the case study results. WaterSET produces results well within the expected range for all quantitative indicators.

CHAPTER 5

Conclusions and Recommendations

The TBL framework developed for this study and described in this report provides a means for utilities to evaluate water supply options and treatment approaches for a single water supply or across a suite of WSOs. A key feature of the approach used here is that the MCDA has been decoupled from the outputs of the TBL model, which allows users to view the quantitative impacts of water supply options separately from the MCDA output. It also provides an opportunity for utilities to determine if, and by how much, different weighting factors may impact the favorability of a specific water supply option or treatment approach. Both the MCDA output and the TBL output have value in communicating risks and impact with stakeholders and therefore WaterSET should provide a means by which this can be developed and presented in a clear, transparent manner to stakeholders.

5.1 Framework Potential

Throughout this project, the team emphasized the development of a novel TBL framework and accompanying tool with the potential to be applied right away as well as the potential to be further refined and improved in the near future. The case study results aptly highlight the direct relevance of the framework to current water supply decision making. Given the trend towards developing alternative WSOs and augmenting water supplies, we envisage that the demand for such a framework that is capable of calculating TBL impacts using unit process information will only increase. Our thorough approach with regards to coding and documentation will allow the necessary improvements.

The following characteristics highlight the great potential of the framework:

- The framework developed for this project provides a flexible approach to TBL analysis because all underlying data can be easily expanded and updated automatically – e.g., cost indices (ENR CCI and BLS), cost curves (engineering textbooks and locally specific data), environmental extensions through CEDA (Suh 2009) and Eora (Lenzen et al. 2013), eGrid through the EPA (EPA 2015) – All aforementioned datasets get updated regularly. The user can modify cost indices and fuel prices to reflect the most current costs. Updates to cost curves and underlying input-output tables and environmental extensions are also possible but do require some coding experience in Matlab as the function needs to be repackaged once data are updated.

- The WaterSET tool provides a relatively quick means for scoping and examining how the role of IPR/DPR could potentially become much more important as water scarcity increases and social acceptability increases.
- WaterSET could be expanded for use in other countries where cost curves are available – the EE-MRIO framework can be adapted to any location/country where input-output tables are available.
- A sensitivity analysis would be useful for utilities where DPR may currently be an unpopular option due to low social acceptability. The model can be used to determine the score and weight at which point DPR becomes more favorable compared to other WSOs and may help guide utilities on where future planning efforts should be focused.

5.2 Future Research

During WaterSET's development, the following potential upgrades to the tool were noted and discussed.

Cost uncertainty and its impact on TBL results A worthwhile future research avenue would be the addition of a Monte Carlo function that allows specifying possible data ranges for all input variables, including the addition of uncertainty margins to each cost curve to better reflect contingency in the planning stage. For this reason, we also make available code in Matlab (packaged as part of the supplementary material accompanying this report) that allows an expert user to run sensitivity analysis at the unit process level to obtain upper and lower estimates for each indicator value for each WSO. More rigorous sensitivity analysis was also attempted in this project (see supplementary files showing positive and negative deviations in CAPEX and OPEX costs) but the Monte Carlo function was not packaged in the final tool as it significantly increased the calculation time which is already quite long due to the very large matrix inversions entailed in the EE-MRIO calculations. The Excel interface is not ideal for this type of simulation. In the future this option should be explored to better evaluate the extent to which cost or other individual input uncertainties could impact each indicator value as well as the final TBL result.

Optimization module In many cases, and especially for larger utilities, it is not a case of simply choosing one WSO over another but about finding the optimum mix to provide a good balance across criteria and future uncertainty. At the moment the user can calculate this manually using a simple weighted aggregate for the criterion. In the future, the tool could be upgraded to address the optimization of water sources, where depending on the weighting of different criteria and the anticipated water demand, a utility could find the optimum water supply mix for their circumstances.

Updating eGrid granularity There is some criticism in the literature that the use of more localised carbon emission factors is worthwhile – see spatial-upstream versus state-wide approach (Fang et al. 2015). Where greenhouse gas estimates need to capture local electricity supply characteristics, additional data and modelling may be necessary.

Use more detailed local economic data through IMPLAN[21] The use of regional input-output tables instead of national input-output tables would significantly improve the ability of the model to simulate local employment and other economic benefits as opposed to national benefits (as does the current model).

Scenarios The type of tool developed here is largely static in the sense that it runs a snapshot comparison between WSOs. A natural extension would be to add a scenario analysis function to allow more dynamic analysis of how TBL results may evolve as the world changes by considering a variety of future scenarios e.g., technologies becoming cheaper, climate change impacts, shifts in social acceptability, etc.

[21] IMPLAN is a highly reputable economic dataset provider, offering datasets at a wide range of regional levels.

APPENDIX A

List of Participants at the Workshops

A.1 Sydney Workshop (UNSW, February 2015)

The attendees of the kick-off workshop in Sydney are listed in Table A-1. The workshop had three principal objectives: to establish limitations of previous frameworks and create a list of desirable features for the framework to be developed as part of this project (Objective 1), to create a shortlist of water supply options to be evaluated (Objective 2), and to discuss the list of proposed indicators. These are elaborated below. Please note that the team took on board all suggestions from workshop attendees, but it has not been possible to implement every single one of these in the final framework and tool delivered in this report.

Table A-1. List of Sydney Workshop Participants with Affiliations and Project Roles (February 12, 2015).

Name	Organization	Organization Role	Project Role
Don Alcock	AWRCE	Knowledge Adoption Manager	Co-Funding partner
Greg Oliver	AWRCE	General Manager	PAC member
Clayton Miechel	Port Macquarie-Hastings	Water & Sewer Process Manager	Utility partner members
Andrew Doig	Port Macquarie-Hastings	Group Manager of Water & Sewer	Utility partner members
Peter Prevos	Coliban Water	Manager System Monitoring and Reporting	Utility partner members
Charles Agnew	Sydney Water	Program Lead - Water Resources	Water utility participant
Muthu Muthukaruppan	City West Water	Manager Water Innovation	Water utility participant
Angela Ganley	City West Water	Senior Projects Development	Water utility participant
David Halliwell	Water Research Australia	Chief Executive Officer	Water utility participant
Gareth Roeszler	Water Research Australia	Program Manager - Research	Water utility participant
Tracey Hamer	MidCoast Water	Planning Engineer	Water utility participant
Pierre Mukheibir	UTS	Assoc. Professor, Sustainable Futures	Water utility participant
Project Team			
Name	**Organization**	**Organization Role**	**Project Role**
Stanford, Ben	Hazen and Sawyer	Director of Applied Research	Lead PI
Stuart Khan	UNSW	Associate Professor	Co-PI
Tommy Wiedmann	UNSW	Associate Professor	Co-PI
Hazel Rowley	UNSW	Senior Research Associate	Principal Researcher
Michalis Hadjikakou	UNSW	Postdoctoral Research Associate	Principal Researcher
Juan Alvarez Gaitan	UNSW	Postdoctoral Research Associate	Technical Review Team
Ian Law	IBL Solutions	Director	Technical Review Team
Michael Short	UniSA/SA Water	Research Fellow	Technical Review Team

Objective 1: Framework discussion and recommendations

On the basis of group discussions held throughout the day of the workshop, the project team compiled the following list of key suggestions where participants and project members felt there was scope to build on/improve existing frameworks:

- **Scale** Scale flexibility is important so that the tool can be of use to water utilities of different sizes. The ability to choose cost relationships on the basis of utility size (i.e., number of household/people supplied) is important.
- **Basic scenario capabilities with variable timescale horizon** Changing population and climate are key variables that need to be captured.
- **Offer both default and fully customisable values/parameters** This could be in the form of an empty spreadsheet along with a fully completed one; or a visual indicator e.g. colour coded 'default' vs custom input.
- **'Hard boundaries' vs. flexible boundaries** Some utilities may have limited interest on upstream impacts in their supply chain. A process-based only calculation method full hybrid IO-LCA whilst also highlighting where and why the results may differ.
- **Provide advice on where a WSO appears to fall short** The report should provide guidance on how users could expand the tool to 'design out' those shortcomings to improve its score. Tool should recommend/suggest more data collection where too many default values have been assigned.
- **Ability to perform analysis with or without social acceptability criteria** This was the subject of extensive discussion at the workshop. Social acceptability is important but not all users will want to include it as a criterion *per se*, preferring to address it outside our framework.
- **Provide sufficient guidance with respect to the MCDA methodology** This will ensure that the process cannot be hijacked by one individual. A documentation feature should ensure that "gaming" of the tool to obtain a desired outcome is limited by providing transparency on the decision making process. The procedure should also take into account that some criteria have an optimum level (e.g., flow) and that further increases after a certain threshold should not be 'rewarded'.
- **Include confidence/error estimates** Wherever possible, an indicator of confidence should be included.
- **Consider the regulatory burden/cost of some options** This refers to costs/time of getting approval, educating the public, etc. As it forms part of the decision-making process for utilities, it makes sense to try to make this part of the framework.
- **Careful selection of criteria and indicators** While a comprehensive list of criteria may be desirable, too many criteria tend to dilute the impact of any one item.
- A careful balance needs to be achieved between reduced water abstraction and reduced return flow to a given water catchment area to avoid negative impacts to downstream water allocations.
- **Existing tools have not done well comparing social and environmental indicators with economic indicators** Utility personnel who try to use this tool will not have necessarily had the training to address the social indicators and therefore they bring consultants familiar with those indicators to assist with the evaluation. This should be made as simple and clear (as well as objective) as possible. Likewise, flexibility in the tool is necessary to bring in case-specific indicators.

Objective 2: Water Supply Options

In this session, three breakout groups were asked to consider current and future water supply options (WSOs) and/or technologies that should be included in the methodology, along with any considerations which may influence their decisions. Individual group suggestions are summarised in Table A-2 which includes a complete list of WSOs, their respective advantages and other considerations.

Table A-1. Water Supply Options.

Water Supply Option	Advantages	Other Considerations/Concerns
DPR/IPR	Expand use of existing supply (retain available resources locally), potentially reduced energy for pumping	Need for new technology /membranes/treatment process, high cost of compliance, energy, public opinion, consider trade-offs between types of IPR/DPR processes (i.e., FAvs non-membrane), consider workplace safety (for all options), consider costs to obtain regulatory approval
Desalination	Uses seawater/brackish water, no freshwater depletion	Brine disposal, energy-intensive, expensive for irrigation, not suitable for most inland areas. Should the tool consider emerging technologies or only those currently used?
New dam (reservoir)	proven & popular, out of sight, flood mitigation, recreation possibilities, hydropower generation	Water quality, hydrological regime change (flood mitigation vs. reduced flow), competing uses (irrigation vs. hydropower), GHGs, location, biological impacts, unintended social, environmental, and political issues
Groundwater pumping	proven & popular, generally available, easy to regulate/implement	Salinity, small-scale, aquifer depletion
Rainwater tanks	Decentralised, provides readily available irrigation for gardens (popular), reduces water bills,	Unpredictable rainfall, Non-potable only, small-scale, energy requirements
Stormwater	Different catchment management required, flooding reduction	Unpredictable rainfall (uncertainty),
Extension of existing supply	Easy option, status quo maintained	Not necessarily future-proof, new pipelines/pumps, threshold effect (step change),
Demand management and leakage reduction	No major construction required, educates community in the long-term, cost-savings to end user, less pumping/energy costs	Restrictions (fines), education, rebate programs, technological change, leakage reduction (staff/monitoring costs)
Dual pipe/purple pipe	Reduces overall potable supply demand, less treatment required than potable reuse	Non-potable only, may have only seasonal customer demand
Water imports	'easy' (quick-fix) solution,	Pumping requirements, expensive

Objective 3: Lists of Key Indicators

In this session, three breakout groups were asked to consider key criteria for assessing different water supply options including justification for their choices and proposing specific indicators that could act as a reliable estimate or proxy for these different criteria (impacts). Tables A-3 through A-5 list environmental, social and economic indicators respectively.

Table A-3. Environmental Indicators List.

Criterion	Importance	Indicators (units)	Further Considerations
Global warming	climate, social acceptance	GHGs (tons CO_2 equivalent)	Specific gases, processes/ sources disaggregation, fugitive emissions
Water Quality	Environmental flows, effects on fauna/flora, potential fines	Eutrophication potential, Ecotoxicity potential, Human toxicity potential, grey water footprint/dilution potential (m_3), natural water flow reduction	
Land use	Wildlife/vegetation, economic impacts,	Land/ecological footprint (hectares),	Local/supply chain land use, opportunity cost of local land use ($), greenfield/brownfield
Waste	Costs, odour/complaints, reputation, air/water/land pollution	Total mass of waste generated (kg)	Types of hazardous/non-hazardous waste, recyclable vs landfill
Water use along the supply chain	Water scarcity considerations, corporate responsibility	Water footprint (e.g., m^3)/scarce water footprint (e.g., m^3)	
Air pollution	Health impacts, complaints/bad reputation	Ozone, PM2.5 or PM10	Odour, noise (dB)

Table A-4. Economic Indicators List.

Criterion	Importance	Indicators (units)	Indicator Sub-Categories
Energy	Costs (economic link), climate, social acceptance, energy scarcity	Energy needed to supply each m^3 of water (kWh/l)	Peak vs. baseload, operational vs. embedded
CAPEX/OPEX	Compulsory	Total costs ($), cost per m^3 of water ($/$m^3$)	Individual costs (especially if major construction/investment required)
Expenditure/revenue time table	Cash flow		Avoided cost, profits
Societal benefit/cost	Good citizenship, social acceptance	Employment generation (number of FTE jobs), income effects, possible costs to the taxpayer	
Life Cycle Cost	Full cost accounting	$ NPV	Administrative, energy, chemicals, labour, spare parts/maintenance, depreciation

Table A-5. Social Indicators List

Criterion	Importance	Indicators (units)	Indicator Sub-Categories
Public/political/institutional acceptance	Social acceptance, feasibility, popularity	YES/NO votes (% acceptance), Willingness to pay ($/m³)	Decision timeframe, upcoming elections?
Liveability	Social amenity, visual satisfaction	Satisfaction survey (utility data?)	Willingness to accept compensation ($) for aesthetic impact/change
Employment	Community benefit from project	Employment generation (number of FTE jobs)	Leakage avoided (local vs. total supply chain employment)
Health impacts	Community concerns	DALY, perceived health impact	
Reliability of water provision	Customer satisfaction, industry/business significance	Flow continuity	Avoided flow restrictions when compared to 'no project' option or present situation

A.2 Los Angeles Workshop (Long Beach, January 2016)

The purpose of the workshop in LA was to involve the U.S. utilities in the development of the tool. The team presented the framework along with screenshots and a step-by-step explanation of the tool prototype. Participants were asked to provide feedback and suggestions to allow better tailoring of the tool to their own circumstances. Attendees of the workshop in Long Beach, California, are listed in Table A-6. The main outcomes and points of discussion are elaborated below. As with the Australian workshop, the project team considered all suggestions from workshop attendees and incorporated into the model and tool as many suggestions as possible.

Table A-6. List of Long Beach Workshop Participants with Affiliations and Project Roles (January, 2016).

Name	Organization	Organization Role	Project Role
Roshanak Aflaki	LA Bureau of Sanitation	Plant Manager	Water utility participant
Charles Bott	Hampton Roads Sanitation District	Director of Water Treatment Technology and Research	Utility partner member
Tom Chesnutt	A&N Technical Services	President	PAC member
Ivana Kajtezovic	Tampa Bay Water	Planning Program Manager	Utility partner member
Megan Plumlee	Orange County Water District	Director of Research	Utility partner member
Mehul Patel	Orange County Water District	Director of Water Production/GWRS	Utility partner member
Project Team			
Name	**Organization**	**Organization Role**	**Project Role**
Ben Stanford	Hazen and Sawyer	Director of Applied Research	Lead PI
Grace Johns	Hazen and Sawyer	Senior Associate	PI
Michalis Hadjikakou	UNSW	Postdoctoral Research Associate	Principal Researcher
Lynn Grijalva	Hazen and Sawyer	Vice President	Quality Control
Alan Karnovitz	Hazen and Sawyer	Senior Associate	Quality Control
Snow, Tama	Hazen and Sawyer	Senior Associate	Quality Control

The following key points emerged during workshops discussions.

OPEX and CAPEX categories These need to be made as intuitive as possible for the user to be able to contribute data. Please note that the option to enter disaggregated costs was subsequently removed as a result of discussions with utility partners as well as results from the utility survey. The user only enters total CAPEX and total OPEX.

Wastewater offset A recurring theme in this project has been the issue of wastewater. Following discussions at this workshop, it was decided to definitively leave wastewater treatment outside the scope of the current framework as this would present a huge technical challenge for both tool developers and users. The tool is focused on potable water supply options.

Defaults vs user-specified The attendees felt that some of the data we are asking for would not be easy to obtain so they recommended adding defaults where possible. The final tool does allow both a 'defaults' option as well as a 'user-specified' options with regards to costs. However, all environmental criteria are based on defaults since users cannot necessarily provide these values. Social criteria are all user-specified.

Water Supply Mix option An important topic discussed at the workshop and also in the final section of this report is the issue of optimising the water supply portfolio using a variety of available options. Some of the attendees suggested adding the capability for the user to create a water supply mix through a weighted 'aggregate of various WSOs'. While certainly worthwhile as a future research avenue, the project team decided that the WaterSET tool was first and foremost to be used to compare one WSO against other WSO variants. For the time being, users may create weighted aggregates of multiple water supply options manually by averaging results from different model runs.

Criteria rethink Many utilities expressed their desire for the tool to include more criteria specific to their context. This was not possible to accommodate but we did add the option in the tool for users to enter additional criteria where they are able to reliably provide their own scores. This kind of flexibility is a defining feature of WaterSET.

Energy for pumping The attendees felt that our consideration of pumping was not detailed enough. We have since fully taken this feedback on board by adding more sophisticated conveyance options allowing the user to specify total head, pumping station capacities and also piping materials and length/diameter.

eGrid state-specific electricity factors The question asked was with regards to the level of spatial detail considered in terms of carbon emissions associated with electricity. Some utilities were keen to know whether the tool could potentially consider county-level electricity carbon emission factors. While, once again, detailed grid configurations provide an obvious benefit in terms of spatial accuracy, as discussed in the final section of this report, the resolution provided by the U.S. Environmental Protection Agency's (EPA) eGrid dataset was the limit to what we could offer for purposes of automation and data confidentiality. We did however add the option of renewable (solar) energy which allows a user to model the extent to which carbon emissions may be reduced through the use of more renewable energy.

Uncertainty The attendees suggested the need for the tool to allow the user to explore the sensitivity of the final results to each main cost category. As discussed in the report, the user can do this manually by varying different costs and recalculating criteria results. The option to conduct sensitivity analysis using the Monte Carlo procedure was explored (and has been implemented in the Matlab version of the tool) but was not included in the final tool because of the prohibitive computational requirements.

Brine management The discussion was whether to explicitly include this as a cost or impact in the tool. As with other such options, this may only be a context-specific issue. We therefore decided to not explicitly build this into the model but include this instead as an optional additional criterion.

APPENDIX B

Industry Survey

Appendix B contains a summary of the main findings of the industry survey in addition to a copy of the questionnaire used in the U.S. and Australian surveys. Please note that this was eventually adapted to an online format. A total of 38 U.S. utilities and 22 Australian utilities completed the survey. The key findings included the following:

- Some utilities are currently considering IPR but the likelihood of considering DPR remains low.
- The availability of detailed cost data at the unit process level is lower than expected, hence the project team focused on sourcing cost curves for unit processes from the literature.
- Even where utilities have cost estimates readily available, these are rarely more accurate than class 3. This means that many of the cost estimates could be around 10-50% off.
- From the given responses, most inputs tend to increase in price from year to year, with the increase normally ranging from 0-5%. In response to this, we have added the option to enter indices (such as ENR and BLS) for all types of costs as well as prices for each individual chemical, thus allowing updating of costs to reflect the most current prices.
- There were considerable deviations in actual yield in relation to design yield, with ocean desalination, groundwater pumping, ASR and surface water pumping registering the highest actual/design yield deviations. Please note that in the majority of cases the actual yield was less than the design yield and the major reason behind this was drought. The only exceptions were Water Imports, IPR, and recycled water, where in some cases actual yield exceeded design yield in response to increased water demand. The tool allows the user to enter both capacity and actual flow rate as a percentage of the capacity. It then uses capacity to estimate impacts arising from capital expenditure and flow rate to estimate impacts arising from operational expenditure thus more accurately reflecting the mode of operation.
- The feedback from the survey was mostly around certain aspects that the respondents felt were not covered or which led to misunderstanding. The last criticism about not explicitly considering environmental, regulatory, social or political aspects of planning is valid. However, the reason why the survey concentrated on costs rather than environmental or social issues was that these other issues had been comprehensively discussed during our face-to-face workshops in Australia and the U.S. – both of which were well attended by utility representatives. The tool offers a range of environmental and social criteria that were selected in consultation with the PAC and the participating utilities and allows the user to add up to two additional criteria to account for utility-specific regional and operational considerations.

Water Utility Survey on Data Availability for 'Triple Bottom Line' Analysis of Water Supply Options

Hazen and Sawyer and UNSW Australia are developing a 'triple bottom line' analysis tool ('TBL tool') to help water utilities choose among alternative water supply options. The TBL tool will quantitatively assess the economic, environmental, and social implications of various water supply options based on a user's utility-specific input data.

This short survey solicits feedback from water utilities to help us design the TBL tool to better serve your needs. In particular, we'd like to know what data are likely to be available to you (as a potential tool user), and how we can design the user interface to facilitate straightforward data entry. To help us develop the underlying model, this survey also asks about the differences between planned and actual water supply based on your experience with completed projects.

Importantly, we are not asking you to provide us with any of your actual data. In addition, the tool itself will be Excel-based or similar, with all data stored on your own PC or network, to negate any confidentiality concerns.

The anonymized, compiled results of this survey will be available to all respondents (utility names and individual responses will not be disclosed in the compiled information).

Utility Information

1. Where is your utility based?
    a. [required] Country: ___ U.S. or ___ Australia
    b. State: ____________
    c. City/Town: __________
2. What is the total resident population of your utility's water supply service area (approx.)? ____
3. Does your utility operate:
    a. Multiple water sources and multiple treatment facilities (water treatment plant)?
    b. Multiple water sources and a single treatment facility?
    c. A single water source and multiple treatment facilities?
    d. A single water source and a single treatment facility?

Please ensure that you respond to all the following questions with reference to your entire utility service system/service area, as opposed to a single plant location

4. How much water (potable and non-potable) does your utility supply to customers each year (approx.)? Please put amount of water including the measurement unit (MGD, MG, MLY).

____

5. Which of the following water supply options does your utility currently use (check all that apply)?

___ Reservoir – Dam
___ Reservoir – River Impoundment
___ Reservoir – Aquifer Storage and Recovery
___ Fresh groundwater pumping
___ Fresh surface water pumping
___ Desalination of seawater
___ Desalination of brackish water
___ Non-potable reclaimed water (dual pipe/purple pipe)
___ Direct potable reuse
___ Indirect potable reuse
___ Rainwater tanks
___ Stormwater use
___ Demand management and leakage reduction
___ Water imports
___ Other, please describe:
____

6. In the list below, please check those unit processes that are used at any of your utility's water treatment plants:

___ Raw Water Storage (Pre-sedimentatio basins)
___ Permanganate pre-oxidation
___ Chlorine dioxide pre-oxidation
___ Powdered Activated Carbon (PAC)
___ Flocculation
___ Sedimentation
___ Lime Clarification/Softening
___ Direct Filtration
___ Sand or Mixed Media Filters
___ Diatomaceous Earth Filters
___ Slow Sand Filters
___ Cartridge Filters (pre-treatment for RO)
___ Membrane Filtration (MF or UF, Polymeric)
___ Membrane Filtration (MF or UF, Ceramic)
___ Dissolved Air Floatation
___ Biological Activated Carbon (BAC)
___ Granular Activated Carbon (GAC)
___ Nanofiltration (NF)
___ Reverse Osmosis (RO)
___ Decarbonation
___ Lime or other calcium addition (stabilization)
___ UV Disinfection
___ UV Advanced Oxidation
___ Free Chlorine Disinfection
___ Ammonia Feed/Chloramination
___ Ozone
___ Fluoride Addition
___ Phosphate Addition (Stabilization)
___ pH control
___ Anion Exchange for NOM (e.g., MIEX)
___ Anion Exchange for Inorganics
___ Cation Exchange for Inorganics
___ Air Stripping
___ Packed Tower Aeration
___ Energy Recovery Devices (RO Systems)
___ Other, please list_____________

7. What other water supply sources might your utility consider in the near future (e.g. the next 20 years)? (Please check all that apply)

   ___ Yes; ___ Maybe | **Reservoir – Dam**
   ___ Yes; ___ Maybe | **Reservoir – River Impoundment**
   ___ Yes; ___ Maybe | **Reservoir – Aquifer Storage and Recovery**
   ___ Yes; ___ Maybe | **Fresh groundwater pumping**
   ___ Yes; ___ Maybe | **Fresh surface water pumping**
   ___ Yes; ___ Maybe | **Desalination of seawater**
   ___ Yes; ___ Maybe | **Desalination of brackish water**
   ___ Yes; ___ Maybe | **Non-potable reclaimed water (dual pipe/purple pipe)**
   ___ Yes; ___ Maybe | **Direct potable reuse**
   ___ Yes; ___ Maybe | **Indirect potable reuse**
   ___ Yes; ___ Maybe | **Rainwater tanks**
   ___ Yes; ___ Maybe | **Stormwater use**
   ___ Yes; ___ Maybe | **Demand management and leakage reduction**
   ___ Yes; ___ Maybe | **Water imports**
   ___ Yes; ___ Maybe | **Other, please describe: ______________________**

Water Production Inputs and Cost Data

Users of the TBL tool will be asked to input data on the expected financial costs (capital and operational) of each water supply option assessed. Default costs can be used if data are unavailable. Cost data could be input either as total costs, or as 'unit costs' (i.e. the costs *per unit of water supplied*).

8. When using the TBL tool, would your utility be able to input the **total costs** or **unit costs** for each water supply option **currently used** by your water utility?

   (a) ___ Yes, total costs only
   (b) ___ Yes, unit costs only
   (c) ___ Yes, either total costs or unit costs
      - ☐ Prefer to enter total costs
      - ☐ Prefer to enter unit costs
      - ☐ No preference
   (d) ___ No, we could not input any cost data

9. For the total or unit cost data of water supply options currently used by your utility, into what level(s) of detail would you be able to break down those costs? (Check all that apply.)

   (a) ___ Breakdown by process (e.g., pre-treatment, filtration, GAC, Lime Clarification, UV Disinfection, Chemical feed system, coagulation and flocculation)

   (b) ___ Breakdown by component (e.g., filter skids, pumps, earthwork, clarifier, screen filter)

(c) ___ Breakdown by type of input (e.g., electricity, type of chemical, labor, membrane)

10. When using the TBL tool, would your utility be able to input the **total costs** or **unit costs** for each water supply option that **would be considered in the future** by your water utility?

    (a) ___ Yes, total costs only
    (b) ___ Yes, unit costs only
    (c) ___ Yes, either total costs or unit costs
        i. ___ Prefer to enter total costs
        ii. ___ Prefer to enter unit costs
        iii. ___ No preference
    (d) ___ No, we could not input any cost data

11. For the total or unit cost data of water supply options that would be considered in the future, into what level(s) of detail would you be able to break down those costs? (Check all that apply.)

    (a) ___ Breakdown by process (e.g., pre-treatment, filtration, GAC, Lime Clarification, UV Disinfection, Chemical feed system, coagulation and flocculation)

    (b) ___ Breakdown by component (e.g., filter skids, pumps, earthwork, clarifier, screen filter)

    (c) ___ Breakdown by type of input (e.g., electricity, type of chemical, labor, membrane)

12. For potential future water supply options, what class of costs would your utility be able to provide?

Check all that apply	Estimate Class	Primary Characteristic: Level of Project Definition (expressed as % of complete definition)	Secondary Characteristic: Expected Accuracy Range
	US Class 5 (AUS Cat 1)	0% to 2%	L: -20% to -50% H: +30% to +100%
	US Class 4 (AUS Cat 2)	1% to 15%	L: -15% to -30% H: +20% to +50%
	US Class 3 (AUS Cat 3)	10% to 40%	L: -10% to -20% H: +10% to +30%
	US Class 2 (AUS Cat 4)	30% to 70%	L: -5% to -15% H: +5% to +20%
	US Class 1 (AUS Cat 5-6)	50% to 100%	L: -3% to -10% H: +3% to +15%

13. Would you prefer to input your utility's data in terms of physical quantities or other relevant units, rather than as costs (e.g. kg or kWh vs chlorine/electricity cost)?

    ____ Yes, prefer physical/other units; ____ No, prefer costs; ____ Indifferent, could do either

14. Do you purchase any capital or operational inputs (e.g. plant, membranes, chemicals, etc.) from foreign manufacturers (even if that manufacturer has a supply agent in your country)?

___ Yes; ____ No

15. If yes, please list the main product(s) purchased and their country of origin (e.g. pumps from Denmark):

Product: ________________________ Origin Country:_____________________________
Product: ________________________ Origin Country:_____________________________
Product: ________________________ Origin Country:_____________________________

Risk and Uncertainty in Input Costs and Water Production

16. For the following operational inputs, by what percentage higher or lower does the price per unit tend to vary from year to year (please include a + or – to indicate the direction of change)?

(a) Electricity ___%; Don't know ___
(b) Non-electrical energy ___%; Don't know ___
(c) Chemicals ___%; Don't know ___
(d) Membranes/filters replacement ___%; Don't know ___
(e) Testing and laboratory ___%; Don't know ___
(f) Other costs, describe:________________________ - ___%
(g) Other costs, describe:________________________ - ___%

17. For each of your utility's existing water supply options, to what extent has the actual amount of water produced differed from the design yield?

Survey should list the answers the respondent gave to Question 4. An example follows:

(a) Indirect potable reuse - Actual is ___ lower or ___ higher than design yield by about _____%

(b) Desalination of seawater - Actual is ___ lower or ___ higher than design yield by about _____%

(c) Fresh groundwater pumping - Actual is ___ lower or ___ higher than design yield by about _____%

18. For each of your utility's existing water supply options, why was the actual yield different from the design yield?

Survey should list the answers the respondent gave to Question 4. Using the same example as above:

(a) Indirect potable reuse - ____ Drought; ____ Water demand different than expected; ____ Issues with one or more unit processes; _____ Other, describe:_____________

(b) Desalination of seawater - ____ Drought; ____ Water demand different than expected; ____ Issues with one or more unit processes; _____ Other, describe:_____________

(c) Fresh groundwater pumping - ____ Drought; ____ Water demand different than expected; ___ Issues with one or more unit processes; ____ Other, describe:______

Please provide any comments about this risk and uncertainty issue:

____

Closing comments

19. Do you have any other comments about this survey or your responses to it?

    ____

Contact details

20. If you would like us to email you a copy of the anonymized, compiled survey results, please enter your email address here (this will only be used to distribute the survey results):

    ____

21. As we continue to develop the TBL tool, we may need to seek further details or clarification on some of your responses. Would you be happy for us to contact you for this purpose?

    [ ] Yes [ ] No

    If yes, please provide your name and preferred contact details (e.g. email address, phone number):

    Name: ____

    Email address: __________________________________

    Phone number: _________________________________

APPENDIX C

WaterSET User Instructions

Appendix C provides user instructions on how to install and run WaterSET.

C.1 Setup and installation

The TBL Tool runs in Microsoft Excel but requires installation of 1) an Excel VBA add-in and 2) a free, downloadable Matlab package. The latter contains 'Matlab Runtime' in addition to the necessary functions to ensure that the Excel add-in can function on any Windows computer, including those without Matlab[22].

Please follow these steps to download and install the required components:

1. Download the 'WaterSET_TBL_ver1.xlsm' and 'MyAppInstaller_mcr.exe' files by clicking here[23] or by copying and pasting the link below into your browser:

   Link: https://drive.google.com/drive/folders/0B6HTj-G8iJEHXzNaTHNEWEhLdG8

   Chrome, Internet Explorer, and web browsers should easily support Google Drive access. However, you may need to update your browser for access to these files on Google Drive. It may also be helpful to log out of any personal Gmail accounts prior to clicking on the link as you may get an error message if you are logged into an account.

   Once the link loads, you will see two folders and two files available for download in the WaterSET download package. Download the 'WaterSET_TBL__US_ver1.xlsm' and 'MyAppInstaller_mcr.exe' files by clicking on them.

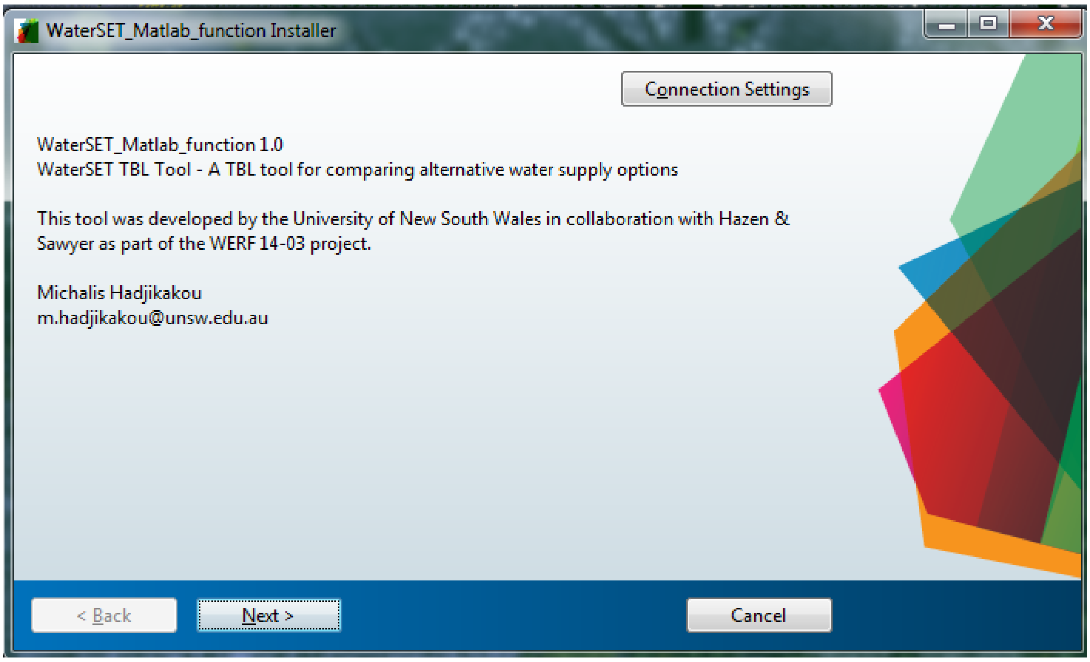
   To download the 'MyAppInstaller_mcr.exe' file, you must select the '64_bit_installer' or the '32_bit_installer' folder. It is advised that you choose the right version of the 'MyAppInstaller_mcr.exe' file depending on whether you are running a 64-bit or 32-bit Microsoft Office. To check whether you should select the 64-bit or 32-bit file, see the links below:

   - Office 2010: https://www.howtogeek.com/howto/24259/beginner-discover-if-youre-running-the-32-or-64-bit-version-of-office-2010/
   - Office 2013 and 2016: https://liberty.service-now.com/kb_view.do?sys_kb_id=7e56d58e358829405af1cb6de5727f5a

   Before proceeding, please make sure to save the 'WaterSET_TBL_ver1.xlsm' file and the appropriate 'MyAppInstaller_mcr.exe' file on your local drive. It is important that both files be saved within the same drive (e.g., the C: drive).

[22] Please note that even on machines where Matlab is already installed, unless the pre-existing version is Matlab 2016a (64-bit), 'Matlab Runtime' must still be installed. In cases where the appropriate version of 'Matlab Runtime' is already installed, the installer will automatically detect this and skip this step.

2. After the two files have been downloaded onto your local drive, run (double-click) the 'MyAppInstaller_mcr.exe' file (either the '64_bit_installer' version or the '32_bit_installer' version depending on which was selected based on your version of Microsoft Office). This should take you to the following screen. Click 'Next' to proceed.

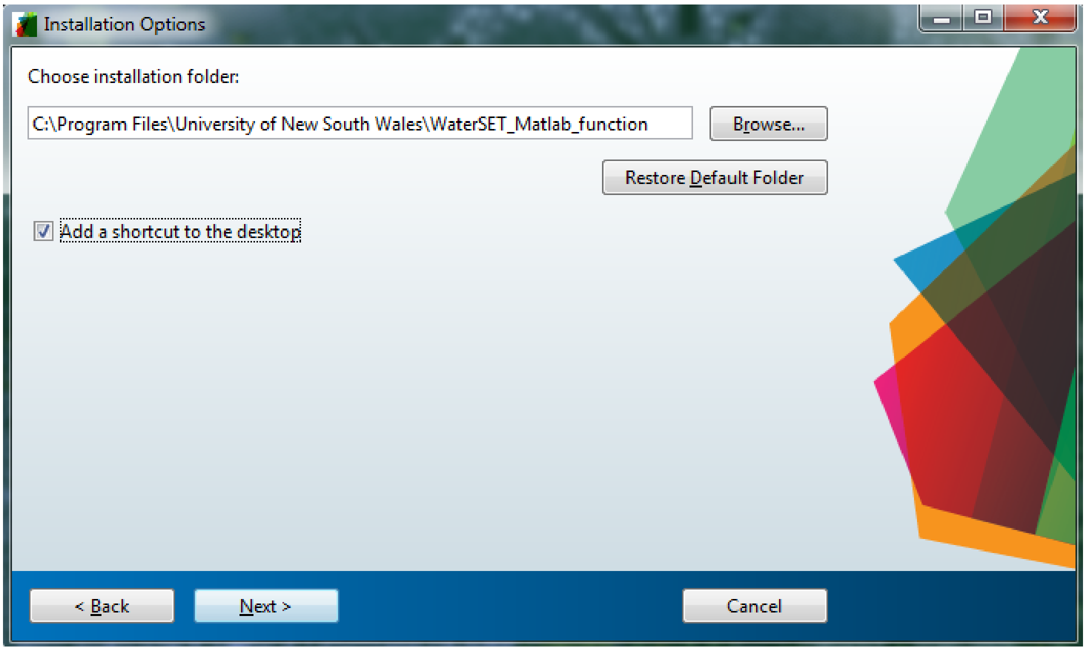


3. Choose the installation folder for the Excel VBA add-in as shown below.

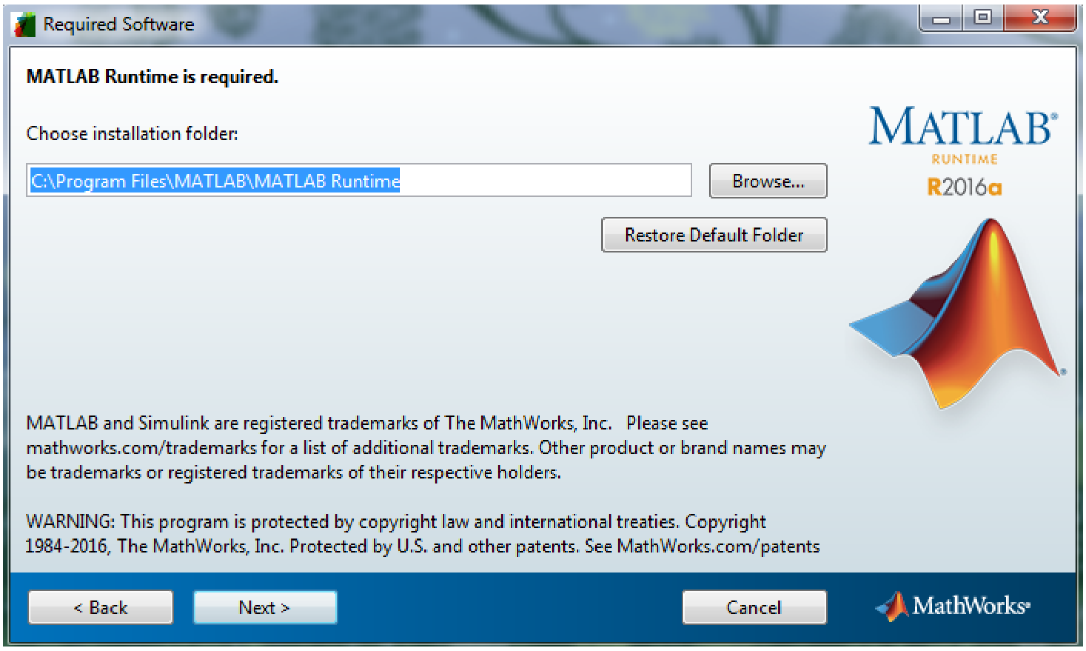
   If the 64-bit version of the 'MyAppInstaller_mcr.exe' file is being used, then the installation folder should be 'C:\Program Files\University of New South Wales\WaterSET_Matlab_function'.

   If the 32-bit version of the 'MyAppInstaller_mcr.exe' file is being used, then the installation folder should be 'C:\Program Files (x86)\University of New South Wales\WaterSET_Matlab_function'.

   It is recommended that you select 'Add a shortcut to the desktop' as shown below to ensure easy access to the function. Click 'Next' to proceed.

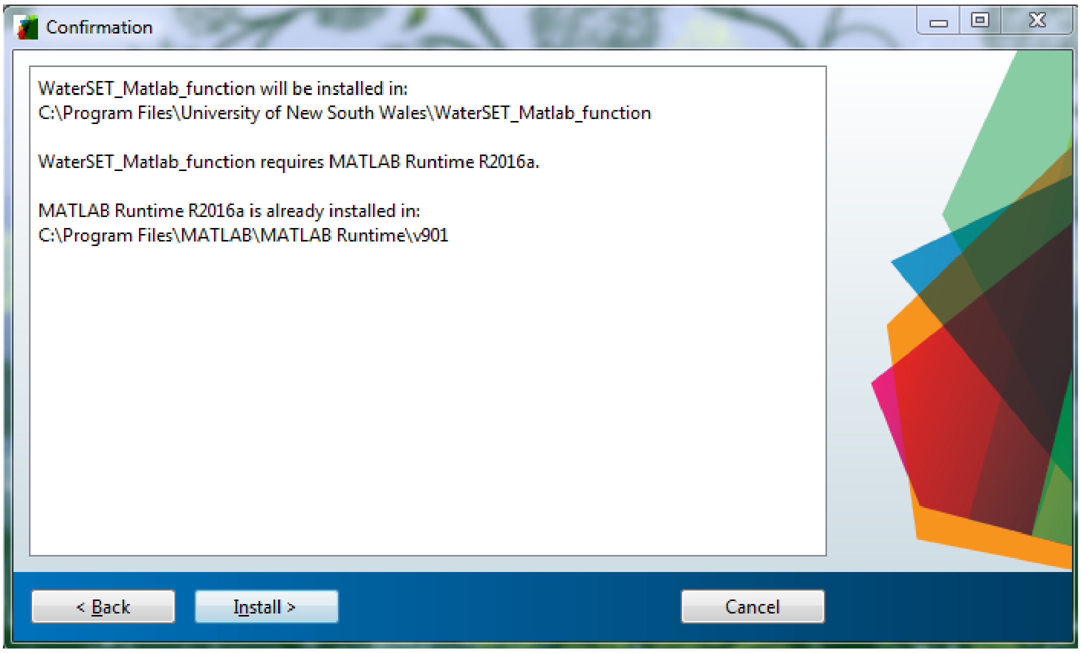


4. During the installation process, ‘MATLAB runtime’ also needs to be installed. It is recommended that you use the default installation folder for this, as shown below[23]. The file path should include ‘Program Files’ for the 64-bit version of the file and ‘Program Files (x86)’ for the 32-bit version. Click ‘Next’ to proceed.

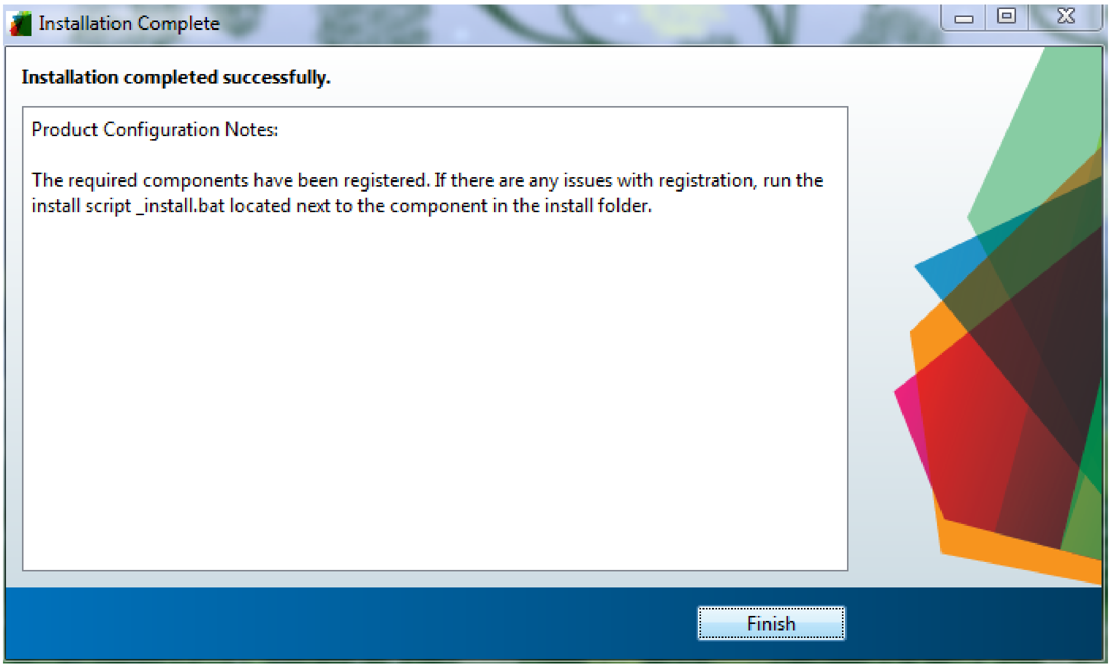


You will then be asked to confirm the installation directories for both the Excel add-in and Matlab Runtime. Click on ‘Install’. The installation will take several minutes, depending on the speed of your machine. Please note that at some point during the installation you will be shown the license agreement where you must select ‘Yes’ before clicking on ‘Next’ to proceed to the ‘Matlab Runtime’ installation.

[23] If only “C:\Program Files” is specified as the installation folder, then you should add the extension “\MATLAB\MATLAB Runtime” to the path.

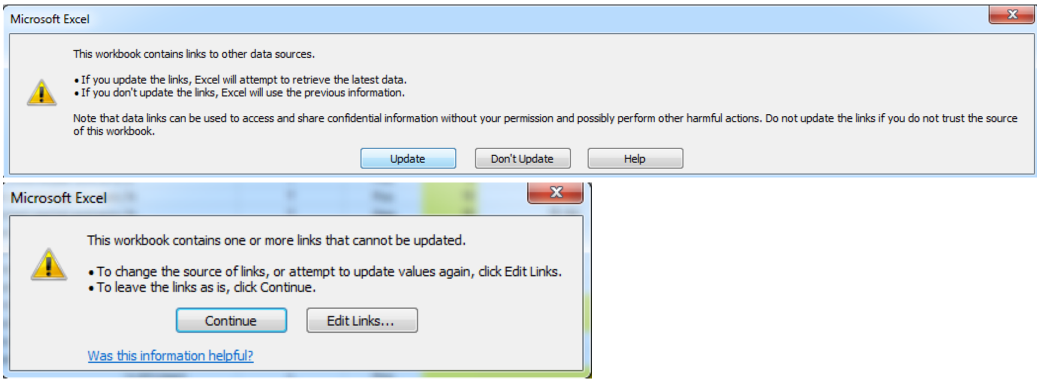


5. On completion the wizard should report that the installation was completed successfully as shown on the screenshot below. Click on 'Finish' to exit the installer. In some cases, you may get a pop up message asking you to reinstall with recommended settings. The only way to address this issue is to go through the installation steps once again[24].



[24] The second installation will take significantly less time as MATLAB Runtime will have already been installed on your machine during the first installation.

6. Open the tool spreadsheet ('WaterSET_TBL_ver1.xlsm') making sure to click on 'Enable', 'Update' and 'Continue' if Excel asks about the enabling of macros and/or updates to links in the spreadsheet[25].



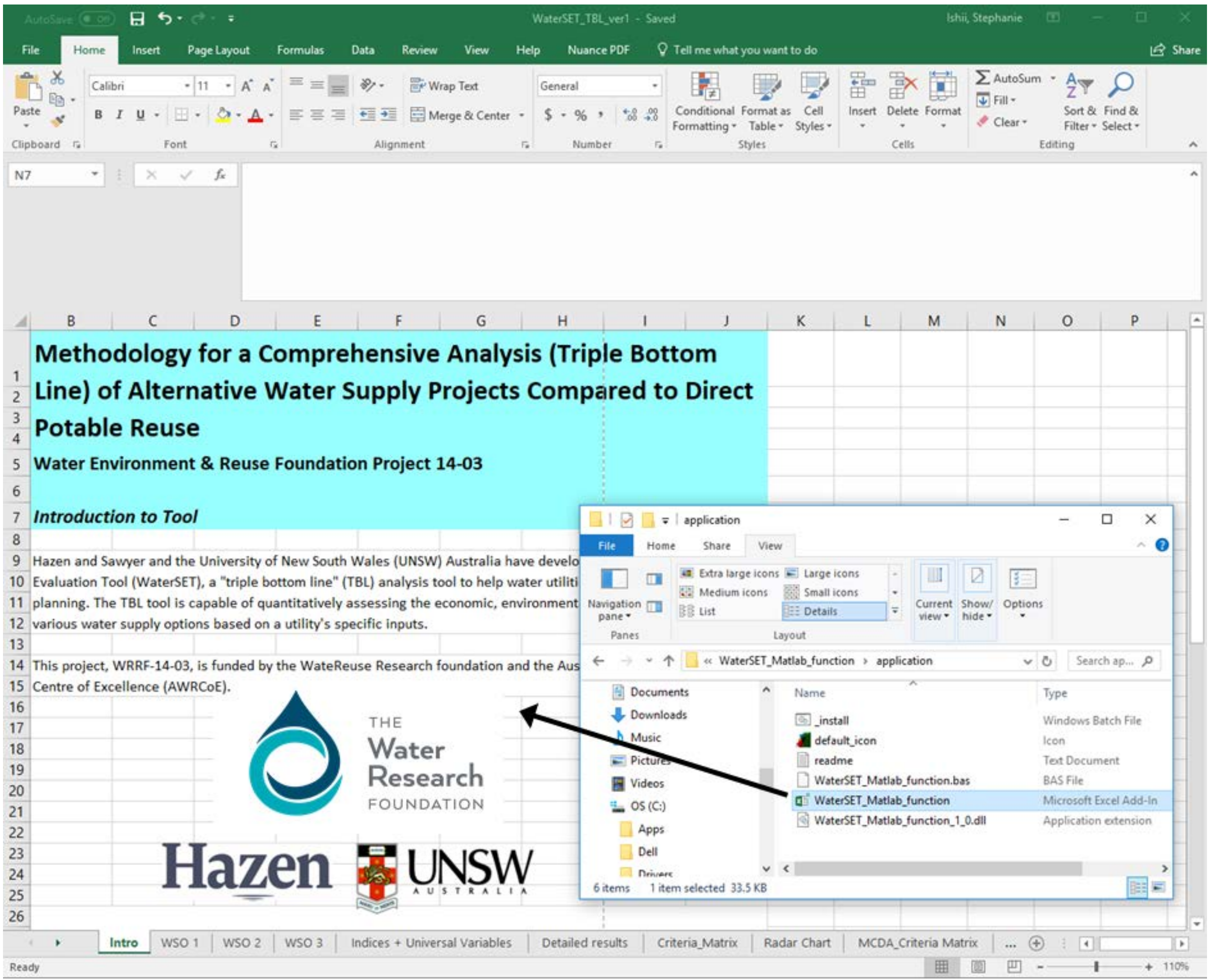
7. Navigate to the folder where the Excel VBA add-in was installed. This should be accessible from your desktop if you selected the 'Add a shortcut to the Desktop' option in step 3 above (simply click once to select the newly created .xla add-in file). If you are not able to go through the desktop shortcut, the .xla file can be found by going to the destination you approved during installation:

   64-bit version:
   C:\Program Files\University of New South Wales\WaterSET_Matlab_function
   32-bit version:
   C:\Program Files (x86)\University of New South Wales\WaterSET_Matlab_function

   The .xla file can be found within the 'application' subfolder. Drag-and-drop the 'WaterSET_Matlab_function.xla' file into the open workbook (as shown below).

8. The tool spreadsheet should now be able to call the Matlab function that provides the computational engine for performing calculations[26].

[25] Depending on your settings, Excel should ask about this when you first load the tool spreadsheet.
[26] If Excel asks you again to enable macros, make sure to click 'Enable'.



9. Navigate to the 'Detailed results' tab and carry out the following operations:

    a. Select cells C2:C36[27] and, if necessary, modify formula so that it reads:

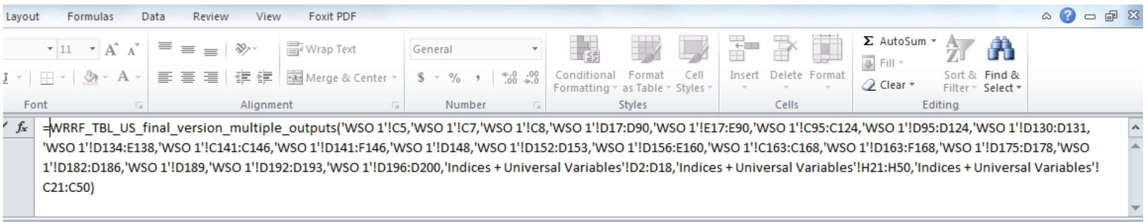
    =WRRF_WaterSET_US_Matlab_version1_0('WSO 1'!C5,'WSO 1'!C7,'WSO 1'!C8,'WSO 1'!D17:D90,'WSO 1'!E17:E90,'WSO 1'!C95:C124,'WSO 1'!D95:D124,'WSO 1'!D130:D131,'WSO 1'!D134:E138,'WSO 1'!C141:C146,'WSO 1'!D141:F146,'WSO 1'!D148,'WSO 1'!D152:D153,'WSO 1'!D156:E160,'WSO 1'!C163:C168,'WSO 1'!D163:F168,'WSO 1'!D175:D178,'WSO 1'!D182,'WSO 1'!D183,'WSO 1'!D184:D187,'WSO 1'!D190,'WSO 1'!D193:D194,'WSO 1'!D197:D201,'Indices + Universal Variables'!D2:D18,'Indices + Universal Variables'!H21:H50,'Indices + Universal Variables'!C21:C50)

    In some cases, the formula may already be correct, in which case no further modification is necessary. If no modification is needed, you may proceed directly to step b. In other cases, Excel might create pre-loaded paths which may not apply to your machine and that you may need to delete as exemplified below.

    ~~='C:\Users\Mcompute\Desktop\WE&RF_TBL_US_final_version\for_testing\WE&RF_WaterSET_US_Matlab_version1_0.xla'!~~=WRRF_WaterSET_US_Matlab_version1_0('WSO 1'!C5,'WSO 1'!C7,'WSO 1'!C8,'WSO 1'!D17:D90,'WSO 1'!E17:E90,'WSO 1'!C95:C124,'WSO 1'!D95:D124,'WSO 1'!D130:D131,'WSO 1'!D134:E138,'WSO 1'!C141:C146,'WSO 1'!D141:F146,'WSO 1'!D148,'WSO 1'!D152:D153,'WSO

[27] It is very important to select all cells at once as this is an array formula.

1'!D156:E160,'WSO 1'!C163:C168,'WSO 1'!D163:F168,'WSO 1'!D175:D178,'WSO 1'!D182,'WSO 1'!D183,'WSO 1'!D184:D187,'WSO 1'!D190,'WSO 1'!D193:D194,'WSO 1'!D197:D201,'Indices + Universal Variables'!D2:D18,'Indices + Universal Variables'!H21:H50,'Indices + Universal Variables'!C21:C50)



b. With cells C2:C36 still selected, press Ctrl+Shift+Enter together – This ensures that the Matlab function is now linked dynamically to the selected cells and will output calculations to these cells every time changes are made to the 'WSO 1' sheet. This final adjustment may take up to a few minutes depending on the speed of your machine.

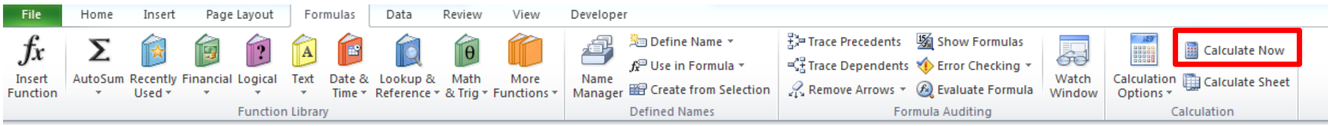
c. If after this operation you get error messages instead of numbers appearing in cells C2:C36, this may be occurring because Excel has not properly registered the add-in. Consider shutting down Excel and restarting your machine. Repeat instructions from step 7. If the function is still not working for you, consider switching to the 32-bit version or the 64-bit version, depending on which one you tried first (irrespective of whether you have a 32-bit or 64-bit Office version).

d. Make sure to repeat the same procedure outline in steps a-c for columns D and E to ensure that sheets 'WSO 2' and 'WSO 3' also become dynamically linked to columns D and E, respectively. The formulae are identical to that followed for cells C2:C36 with the only difference being that the inputs source sheet needs to be changed from 'WSO 1' to 'WSO 2' (for D2:D36) and 'WSO 3' (for E2:E36). The pre-loaded cell formulae should already reflect this.

C.2 Using the Model – Basic Operation Tips

After following the installation process outlined previously, you may run the model by modifying inputs in the '**WSO 1-3**' tabs (all cells highlighted in yellow represent possible input cells related to the WSO being evaluated – for more details see main report, Section 3.5), as well as in the **'Indices + Universal Variables'** tab, the latter allowing you to modify chemical costs and purity as well as to specify cost indices used for converting costs to the present day. Modifications to the '**Indices + Universal Variables**' tab are optional but should allow for a more site-specific estimation of life cycle costs, as well as all associated environmental and other impacts, if the information is available.

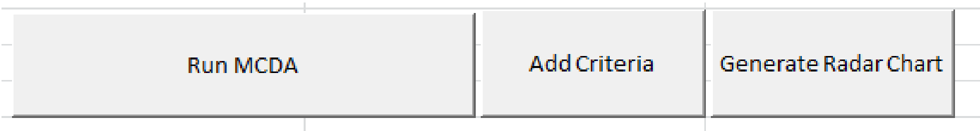
Please note that the spreadsheet calculation mode has been set to manual to prevent the tool from automatically recalculating outputs every time a new input or change is made by the user. The manual mode allows you to freely add and change inputs while the tool remains idle. When you are satisfied with your inputs on the **'WSO 1-3'** and **'Indices + Universal Variables'** tabs, click on the '**Formulas**' tab on the Excel Ribbon and then click on '**Calculate Now**' (as shown below). The tool will now carry out a recalculation of all criteria based on the newly specified inputs. This may then take a few minutes depending on the speed of your machine.



Once the tool has completed its calculations, go to the **'Criteria_Matrix'** tab. The **'Criteria Matrix**' tab collects and displays all quantitative criteria[28] in a table (i.e., that calculated by the tool based on user inputs for WSO 1-3), as well as provides a place for users to enter values for all qualitative criteria. Additionally, users may input weights for each of the criteria as an indication of how important an individual criterion is in the decision making process. Every time you make changes to your inputs in the '**WSO 1-3**' and **'Indices + Universal Variables'** tabs and click on '**Calculate Now**', the tool harvests the new model outputs from the '**Detailed results**' tab and displays the updated values in the '**Criteria Matrix**' tab. Please note that this tool only includes one **'Criteria Matrix'** tab, but that the sensitivity of results to different criteria weightings and/or qualitative criteria inputs can be tested by running the model with one set of values in the **'Criteria Matrix'** tab, saving the results, and then rerunning the model with a new set of values in the **'Criteria Matrix'** tab.

The '**Criteria Matrix**' tab becomes the basis for further analysis and can be used to conduct a multi-criteria decision analysis (MCDA) after inputting user-specified weights for all criteria, scores for qualitative criteria, and incorporating new criteria if desired (click the **'Add Criteria'** button for more information).

Once criteria weightings and qualitative criteria scores have been input, click the **'Run MCDA'** button to evaluate each of the water supply options based on WSO inputs and criteria weightings. Click the **'Generate Radar Chart'** button to see how the water supply options compare without inclusion of criteria weightings.



Criteria weightings must be entered on the **'Criteria Matrix'** tab in order to run the MCDA. The higher the assigned weight for an individual criterion, the higher the influence that criterion has on the final MCDA scores. The pie chart at the bottom of the **'Criteria_Matrix'** tab may be used to facilitate input of weightings, as it shows the relative importance being assigned to environmental, economic, and social groupings of criteria. The square button next to each criterion may be clicked for more information about how the criterion is defined. For the criteria requiring user-defined score inputs for each water supply option (i.e., those with score cells highlighted in yellow), the buttons may also be clicked for more information on how to score the criteria.

The radar chart is available in the '**Radar Chart**' tab. Please note that this will only display the ten quantitative criteria. The comparison is normalised on the basis of WSO 1, which is always taken as the baseline (i.e., a score of 1 for all quantitative criteria).

MCDA results can be accessed via the '**MCDA Criteria Matrix**' tabs. The highest number always represents the best option. The actual score is not meaningful in an absolute sense and is only intended to provide a relative comparison between WSOs.

Each time you re-run the MCDA or generate a new radar chart, the '**Radar Chart'** and '**MCDA Criteria Matrix**' tabs should update automatically. Make sure to click on 'Calculate Now' every time you change any inputs in the WSO 1-3 tabs to ensure that the model recalculates outputs based on your new inputs. If you're only changing the criteria weightings (i.e., no changes to WSO 1-3), you can simply click "Run MCDA" without recalculating the worksheet every time.

The user can review the '**Detailed Results**' tab to see an estimate of energy requirements, capital costs (CAPEX), and/or operation and maintenance costs (OPEX) breakdowns for each WSO.

[28] These correspond to the 10 first rows in the 'Detailed results' tab.

APPENDIX D

U.S. Case Study Inputs and Outputs

D.1 Hampton Roads Sanitation District, Virginia, United States

Table D-1. Hampton Roads Sanitation District Inputs for WSO 1 (carbon-based treatment).

Category	WSO 1: Carbon-Based Treatment
New or existing plant?	New
New plant or expansion capacity	1 mgd
Liquid alum feed	12.5 lb/hr/unit; 1 unit
Polymer feed	13.76 lb/day/unit; 1 unit
Sodium hydroxide feed	453.6 lb/day/unit; 1 unit
Aqua ammonia feed	10 gal/day/unit; 1 unit
Rapid mix G = 900/s	240 gal/unit; 4 units
Flocculation: Horizontal paddle systems G = 80/s	922.46 ft^3/unit; 6 units
Rectangular clarifier	2,125 ft^2/unit; 2 units
Gravity filter structure	57 ft^2/unit; 4 units
Filtration media – rapid sand	1 mgd/unit; 1 unit
Filter backwash pumping	25 gpm/unit; 4 units
Surface wash system	57 ft^2/unit; 4 units
Air score wash	57 ft^2/unit; 4 units
Finished Water Pumping TDH =30ft	1 mgd/unit; 1 unit
Finished Water Pumping TDH =100ft	1 mgd/unit; 1 unit
Raw water pumping TDH = 30ft	1 mgd/unit; 1 unit
Raw water pumping TDH = 100ft	1 mgd/unit; 1 unit
In-plant pumping TDH = 35ft	1 mgd/unit; 1 unit
In-plant pumping TDH = 75ft	1 mgd/unit; 1 unit
Ozone	1 mgd/unit; 1 unit
UV advanced oxidation (UV/H2O2)	0.20 mgd/unit; 1 unit
BAC – 10min EBCT	1 mgd/unit; 1 unit
Administrative, laboratory, and maintenance building	1 mgd/unit; 1 unit
Caustic soda (sodium hydroxide)	300 lb/day
Sodium hypochlorite liquid chlorine	170 lb/day
Liquid oxygen (LOX)	200 lb/day
Liquid alum feed – 50% solution	250 lb/day
Polymer (Polydyne SE1179 polymer)	8.5 lb/day
Sodium hydroxide – 50% solution (pH control)	310 lb/day
Ammonia (chloramines)	90 lb/day
Cost type (default or user defined)	Default
Cost year	2016
Plant service life	30 years
Annual real interest rate	5%
Electricity purchased from grid	100%

Table D-2. Hampton Roads Sanitation District Inputs for WSO 2 (membrane-based treatment).

Category	WSO 1: Carbon-Based Treatment
New or existing plant?	New
New plant or expansion capacity	1 mgd
Sulfuric acid feed	12.74 gal/day/unit; 1 unit
Sodium hydroxide feed	453.6 lb/day/unit; 1 unit
Lime feed	50 lb/day/unit; 1 unit
Aqua ammonia feed	6 gal/day/unit; 1 unit
Finished Water Pumping TDH =30ft	1 mgd/unit; 1 unit
Finished Water Pumping TDH =100ft	1 mgd/unit; 1 unit
Raw water pumping TDH = 30ft	1 mgd/unit; 1 unit
Raw water pumping TDH = 100ft	1 mgd/unit; 1 unit
In-plant pumping TDH = 35ft	1 mgd/unit; 1 unit
In-plant pumping TDH = 75ft	1 mgd/unit; 1 unit
UV advanced oxidation (UV/H2O2)	1 mgd/unit; 1 unit
MF/UF	1 mgd/unit; 1 unit
NF/RO	1 mgd/unit; 1 unit
Administrative, laboratory, and maintenance building	1 mgd/unit; 1 unit
Conventional treatment (standard WTP)	1 mgd/unit; 1 unit
Caustic soda (sodium hydroxide)	300 lb/day
Sodium hypochlorite liquid chlorine	170 lb/day
Lime	50 lb/day
Sulfuric acid	100 lb/day
Sodium hydroxide – 50% solution (pH control)	50 lb/day
Ammonia (chloramines)	45 lb/day
Antiscalant – 100%	18 lb/day
Hydrogen peroxide – 50%	75 lb/day
Cost type (default or user defined)	Default
Cost year	2016
Plant service life	30 years
Annual real interest rate	5%
Electricity purchased from grid	100%

Table D-3. Hampton Roads Sanitation District Detailed Results Outputs for WSOs 1 and 2.

Type	Criterion	WSO 1: Carbon-Based Treatment	WSO 2: Membrane-Based Treatment
Matlab Criteria (used in MCDA to determine EVAMIX score), per MGD	Life cycle cost	5.25	5.16
	U.S. resident income	3.63	4.01
	Variable cost percentage	35.59	48.85
	Cost of imported capital and annual O&M as percentage of total	16.08	14.11
	Carbon footprint	16.47	19.82
	Water footprint	5,640.38	6,335.97
	Eutrophication potential	0.00	0.00
	Ecotoxicity potential	1.91	1.62
	National jobs created during construction and operation	0.10	0.10
	Effect of potential pollution caused by WSO on human health	*No user input*	*No user input*
Energy, kWh total	Annual plant electricity requirements	4,060,137.80	6,680,125.05
	Annual plant electricity requirements per MGD	4,060,137.80	6,680,125.05
	Annual conveyance electricity	*No user input for conveyance*	*No user input for conveyance*
	Annual conveyance electricity per MGD	*No user input for conveyance*	*No user input for conveyance*
Annual CAPEX estimates, 2012 USD total	Sitework	2,665.42	2,991.61
	Equipment	197,277.64	183,622.66
	Concrete	13,801.69	20,509.88
	Steel	13,763.99	20,040.51
	Pipes & valves	102,498.64	38,494.01
	Instrumentation	33,891.70	12,014.11
	Housing	51,128.70	33,022.21
	Yard piping	49,739.86	38,805.82
	Landscaping	24,869.93	19,402.91
	Site Electrical	99,479.72	77,611.64
	Engineering Legal	340,780.20	265,868.37
	PVC pipe (conveyance)	*No user input for conveyance*	*No user input for conveyance*
	Ductile Iron (conveyance)	*No user input for conveyance*	*No user input for conveyance*
	Labour	183,094.02	155,944.99
Annual O&M estimates, 2012 USD total	Electricity	407,084.93	665,595.70
	Natural Gas	0.00	0.00
	Diesel	0.00	889.55
	Maintenance	99,819.44	244,259.23
	Inorganic chemicals	163,130.18	55,082.93
	Chlorine & alkalies	182,819.38	184,334.13
	Organic chemicals	5,429.38	0.00
	Black carbon	0.00	0.00
	Labour	406,932.66	550,848.56

D.2 Western Utility, United States

Table D-4. Western Utility Inputs for WSO 1 (increased groundwater recharge).

Category	WSO 1: Increased Groundwater Recharge
New or existing plant?	Existing
New plant or expansion capacity	30 mgd
Sodium hypochlorite generated offsite	1,299 lb/day/unit; 4 units
Polymer feed	85 lb/day/unit; 1 unit
Sulfuric acid feed	6,600 gal/day/unit; 3 units
Lime feed	2,000 lb/day/unit; 4 units
UV advanced oxidation (UV/H2O2)	30 mgd/unit; 1 unit
MF/UF	30 mgd/unit; 1 unit
NF/RO	30 mgd/unit; 1 unit
Administrative, laboratory, and maintenance building	30 mgd/unit; 1 unit
Sodium hypochlorite liquid chlorine	18,821 lb/day
Dry alum (coagulation) – 48%	1.30 lb/day
Polymer (Polydyne SE1179 polymer)	25.00 lb/day
Lime	5,862.00 lb/day
Sulfuric acid – 93% solution (pH control)	4,095.00 lb/day
Sodium hydroxide – 30%	102 lb/day
Citric acid – 50%	63 lb/day
Hydrogen peroxide – 50%	1,411 lb/day
Estimated total head loss from source to WTP	70 ft
Pump efficiency (default = 0.6)	0.6
Cost type (default or user defined)	Default
Cost year	2016
Plant service life	30 years
Annual real interest rate	5%
Electricity purchased from grid	100%

Table D-5. Western Utility Inputs for WSO 2 (new desalination facility).

Category	WSO 2: New Desalination Facility
New or existing plant?	New
New plant or expansion capacity	50 mgd
Administrative, laboratory, and maintenance building	50 mgd/unit; 1 unit
SWRO (WTP)	50 mgd/unit; 1 unit
Caustic soda (sodium hydroxide)	10 mg/L
Sodium hypochlorite liquid chlorine	2 mg/L
Sulfuric acid – 93% solution (pH control)	200 mg/L
Fluoride	1 mg/L
Citric acid – 50%	3 mg/L
Estimated total head loss from source to WTP	70 ft
Pump efficiency (default = 0.6)	0.6
Cost type (default or user defined)	Default
Cost year	2016
Plant service life	30 years
Annual real interest rate	5%
Electricity purchased from grid	100%

Table D-6. Western Utility Detailed Results Outputs for WSOs 1 and 2.

Type	Criterion	WSO 1: Increased Groundwater Recharge	WSO 2: New Desalination Facility
Matlab Criteria (used in MCDA to determine EVAMIX score), per MGD	Life cycle cost	1.87	2.68
	U.S. resident income	1.44	1.92
	Variable cost percentage	71.77	73.75
	Cost of imported capital and annual O&M as percentage of total	23.82	21.59
	Carbon footprint	8.63	14.72
	Water footprint	2,690.24	4,232.78
	Eutrophication potential	0.00	0.00
	Ecotoxicity potential	0.63	0.84
	National jobs created during construction and operation	0.05	0.08
	Effect of potential pollution caused by WSO on human health	*No user input*	*No user input*
Energy, kWh total	Annual plant electricity requirements	52,336,631.01	281,385,214.61
	Annual plant electricity requirements per MGD	1,744,554.37	5,627,704,29
	Annual conveyance electricity	*No user input for conveyance*	*No user input for conveyance*
	Annual conveyance electricity per MGD	*No user input for conveyance*	*No user input for conveyance*
Annual CAPEX estimates, 2012 USD total	Sitework	0.00	0.00
	Equipment	1,737,556.84	4,233,345.41
	Concrete	0.00	0.00
	Steel	0.00	0.00
	Pipes & valves	13,664.71	0.00
	Instrumentation	15,166.85	196,589.13
	Housing	69,081.38	406,812.92
	Yard piping	231,807.01	517,015.28
	Landscaping	115,903.51	258,507.64
	Site Electrical	463,614.03	1,034,030.56
	Engineering Legal	1,588,167.80	3,542,200.94
	PVC pipe (conveyance)	*No user input for conveyance pipe*	*No user input for conveyance pipe*
	Ductile Iron (conveyance)	*No user input for conveyance pipe*	*No user input for conveyance pipe*
	Labour	952,009.55	1,380,361.28
Annual O&M estimates, 2012 USD	Electricity	5,172,353.35	28,307,352.59
	Natural Gas	0.00	0.00
	Diesel	0.00	0.00
	Maintenance	1,892,671.86	7,735,634.78
	Inorganic chemicals	235,480.62	2,913,531.99
	Chlorine & alkalies	18,288,972.88	27,277,836.41
	Organic chemicals	15,968.75	0.00
	Black carbon	0.00	0.00
	Labor	2,557,096.87	3,046,621.40

APPENDIX E

Australian Case Study

Coliban Water, a state-owned regional water corporation in the Australian state of Victoria, participated in the development and use of WaterSET to provide valuable insights into how potable reuse schemes compare against the current supply option on a triple bottom line basis. Coliban Water previously invested in a water recycling plant (the Bendigo Water Factory) that produces high quality recycled water for non-potable reuse applications. Strategically, from a long-term security and diversification of supply perspective, Coliban Water is interested in exploring whether the Bendigo Water Factory could form part of a potable reuse scheme in the future, although neither DPR nor IPR are currently required to maintain a secure water supply for Bendigo, and are not supported under current government policy. Coliban Water's interest in further investigating reuse as a water supply option stems from the potential to maximize the return on investment in the current water recycling assets and to work towards having a comprehensive range of responses to any future climate shifts in the Bendigo region. The purpose of this exercise was not to recommend investment in any of the modelled alternative water supply options, but rather to explore how available water supply options compare across the WaterSET criteria to gain an overall better understanding of the potential options. The outcomes of this evaluation are academic in nature and do not reflect a formal position of Coliban Water on potable reuse.

The Coliban Water case study presented herein compares three water supply options, all running at full capacity. Information for these WSOs was input based on operational data, previous studies, and published literature as needed.

- WSO 1: Status quo (126 ML/day; 6.7 MGD)
    - Customers in Bendigo are supplied from one of three raw water sources. The primary source of raw water is a series of reservoirs near the township of Kyneton, approximately 75 km to the south of Bendigo. The secondary source of water is an allocation of the water in Lake Eppalock, located within the greater Bendigo region. The third supply option is a 42 km pipeline from the Goulburn River catchment. Coliban Water has developed operational rules to decide which water source is used to service its customers, based on the current resource situation and climate forecast.

      Inputs for this WSO assume that there is a situation where Bendigo is under water stress and relies 100% on the Goulburn River system. Once the raw water is conveyed from the Goulburn River catchment, it is treated via chlorination, ozone, lime softening, permanganate addition, microfiltration, and biofiltration, and subsequently distributed through the Coliban Water network. In addition to conveyance and treatment requirements for the raw water supply, this WSO also includes inputs related to subsequent wastewater treatment and Class A reclaimed water production at the Bendigo Water Factory in order to compare it to potable reuse options.
- WSO 2: Indirect potable reuse (20 ML/day; 5.3 MGD)
    - The premise of this WSO is that the water produced by the Bendigo Water Factory could be diverted to a reservoir or lake to be reused as a raw water source for drinking water production. This requires an expansion of the Water Factory and additional piping. The expansion is assumed to include ultrafiltration, reverse osmosis, chlorination, and UV

disinfection. Importantly, this WSO allows for the production of the status quo water supply (WSO 1) to be reduced.

- WSO 3: Direct potable reuse (20 ML/day; 5.3 MGD)
    - WSO 3 involves upgrading the Bendigo Water Factory to the standard of a drinking water treatment plant, including ultrafiltration, reverse osmosis, lime softening, chlorination, UV disinfection, and ammonia addition. This option also requires an investment in pumping capabilities to inject the treated water into the Coliban Water network.

The WSOs were first compared in an unweighted manner using the radar chart in Figure E-1. Results show that the lifecycle cost, water footprint, and carbon footprint of WSO 2 (IPR) are more than two times more favorable than WSO 1 (status quo WTP) and also slightly more favorable than WSO 3 (DPR). These results can be explained by the fact that the electricity required for plant operation in WSO 1 is approximately equal to WSOs 2 and 3, but it requires greater electricity use for raw water conveyance from the surface water supply. The large conveyance-based energy requirement of WSO 1 resulted in a burden that was reflected in the lifecycle cost, water footprint, and carbon footprint relative to WSOs 2 and 3.

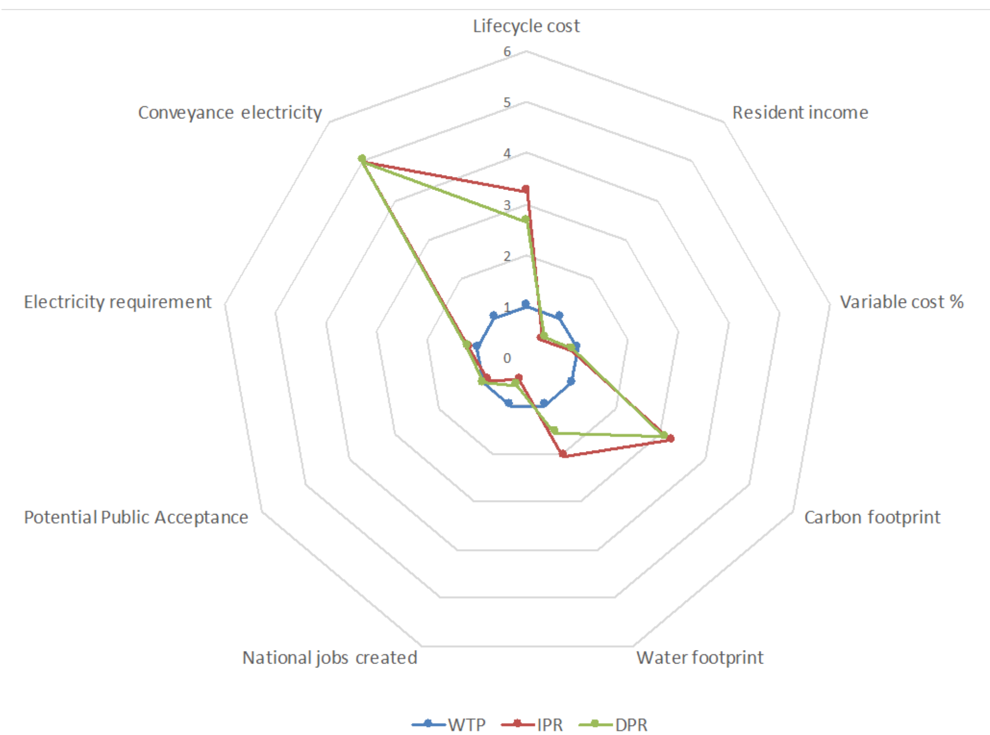


Figure E-1. Radar Chart Generated from Coliban Water inputs for Three Different Water Supply Options.

The three WSOs were then compared using criteria weightings. Weightings were decided by using a survey among Coliban Water staff, for which ten responses were received. The weightings used in the model are the average weighting per criterion based on the collected survey responses. Figure ES-2 shows how the cumulative weightings of economic, environmental, and social criteria compared. The results of MCDA are shown in Figure ES-3, in which WSO 2 (IPR) is shown to be the highest ranked and most favourable of the three WSOs under consideration. Using WaterSET's outputs and Coliban Water's criteria weightings, WSO 1, the status quo WTP, was ranked as the least favorable option.

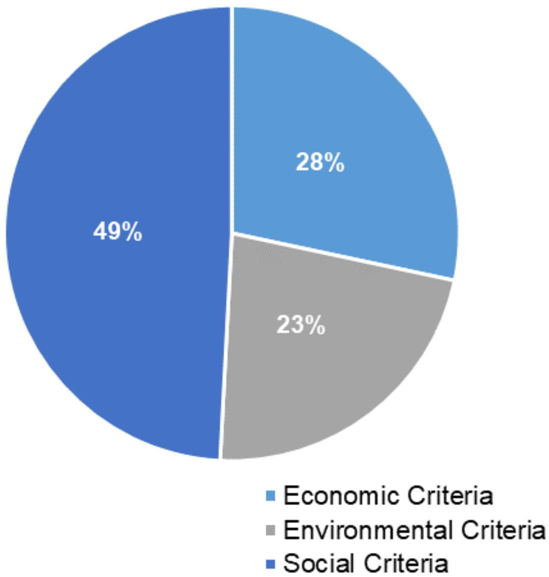


Figure E-2. Relative Importance of Criteria Categories in the MCDA Based on Coliban Water Criteria Weightings.

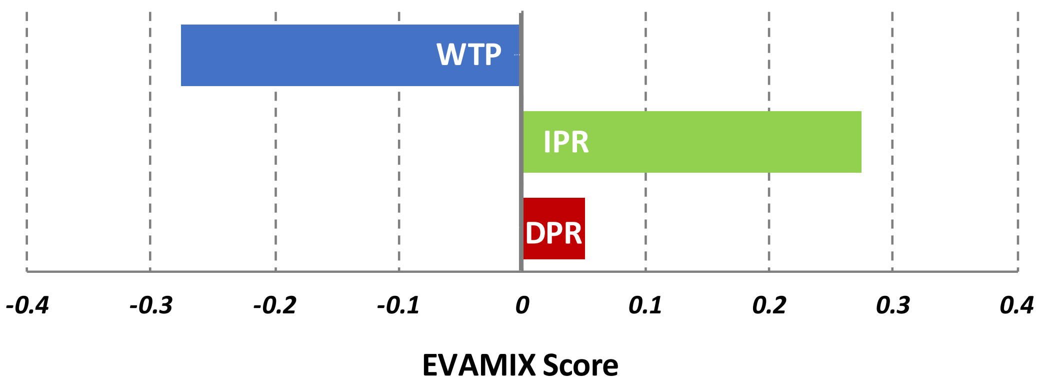


Figure E-3. MCDA Results for Coliban Water Inputs Regarding Three Different Water Supply Options and Criteria Weightings.

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THE
Water
Research
FOUNDATION

1199 North Fairfax Street, Suite 900
Alexandria, VA 22314-1445
www.werf.org | werf@werf.org

6666 West Quincy Avenue
Denver, CO 80235-3098
www.waterrf.org | info@waterrf.org