Carbon footprint of water reuse and desalination: a review of greenhouse gas emissions and estimation tools

Pablo K. Cornejo, Mark V. E. Santana, David R. Hokanson,
James R. Mihelcic and Qiong Zhang

ABSTRACT

As population and water demand increase, there is a growing need for alternative water supplies from water reuse and desalination systems. These systems are beneficial to water augmentation; however, there are concerns related to their carbon footprint. This study compiles the reported carbon footprint of these systems from existing literature, recognizes general trends of carbon footprint of water reuse and desalination, and identifies challenges associated with comparing the carbon footprint. Furthermore, limitations, challenges, knowledge gaps, and recommendations associated with carbon footprint estimation tools are presented. Reverse osmosis (RO) technologies were found to have lower CO_2 emissions than thermal desalination technologies and the estimated carbon footprint of seawater RO desalination (0.4–6.7 kg CO_2eq/m^3) is generally larger than brackish water RO desalination (0.4–2.5 kg CO_2eq/m^3) and water reuse systems (0.1–2.4 kg CO_2eq/m^3). The large range of reported values is due to variability in location, technologies, life cycle stages, parameters considered, and estimation tools, which were identified as major challenges to making accurate comparisons. Carbon footprint estimation tools could be improved by separating emissions by unit process, direct and indirect emissions, and considering the offset potential of various resource recovery strategies.

Key words | carbon footprint models, climate change, life cycle assessment, reverse osmosis, sustainability, water reclamation

Pablo K. Cornejo
Mark V. E. Santana
James R. Mihelcic
Qiong Zhang (corresponding author)
Department of Civil and Environmental Engineering,
University of South Florida,
4202 E. Fowler Avenue,
Tampa FL 33620,
USA
E-mail: *qiongzhang@usf.edu*

David R. Hokanson
Trussell Technologies Inc.,
232 N Lake Ave,
Pasadena,
CA 91101,
USA

INTRODUCTION

Water and wastewater utilities are increasingly adapting to climate variability and associated supply reliability issues (Major *et al.* 2011). In addition, many parts of the world are facing periods of prolonged drought, increasing population, and urbanization which place pressure on traditional water resources (Zimmerman *et al.* 2008; Padowski & Jawitz 2012). Accordingly, some locations have turned to the implementation of water reuse and desalination systems to meet growing water demands. While water reuse and desalination are beneficial to water managers, in some cases these systems are more energy intensive than conventional water supply and treatment, thus raising concerns about their carbon footprint. For instance, the embodied energy of drinking water provision in Tampa, Florida was estimated to be 7.2 MJ/m^3, whereas the embodied energy of water reuse and seawater reverse osmosis (RO) desalination were approximately 13–18 and 24–42 MJ/m^3, respectively (Lyons *et al.* 2009; Stokes & Horvath 2009; Pasqualino *et al.* 2010; Santana *et al.* 2014).

Many local and state governments have taken action to mandate a reduction in greenhouse gas (GHG) emissions to address the problem of elevated carbon footprints and climate change impacts. For example, more than 825 cities are participating in the United States Mayors Climate

doi: 10.2166/wrd.2014.058

Protection Agreement, which would reduce GHG emissions in accordance with Kyoto Protocol goals (Newman *et al.* 2009). Other measures, such as Assembly Bill 32 in California, require a reduction in GHGs to 1990 levels by 2020, whereas Seattle's Climate Change Action Plan seeks to achieve net zero emissions by 2050 (Foster *et al.* 2013).

GHG emissions from water reuse and desalination systems come from: (1) direct emissions from on-site sources (referred to as Scope 1), (2) indirect emissions associated with off-site energy production (referred to as Scope 2), and (3) other indirect emissions (i.e. production of chemicals, materials, fuels, etc.) (referred to as Scope 3) (Huxley *et al.* 2009). The carbon footprint is defined as the sum of individual GHG emissions, in which carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are expressed in carbon dioxide equivalents (CO_2eq) by converting CH_4 and N_2O emissions using their global warming potential (IPCC 2006; Mihelcic *et al.* 2013).

A number of studies have assessed the carbon footprint and/or GHG emissions of water reuse and desalination systems (Lundie *et al.* 2004; Stokes & Horvath 2006, 2009; Lyons *et al.* 2009; Muñoz *et al.* 2009, 2010; Meneses *et al.* 2010; Pasqualino *et al.* 2010; de Haas *et al.* 2011; Shrestha *et al.* 2011). Additionally, various estimation tools have been developed to assess the carbon footprint of water and wastewater systems (Stokes & Horvath 2006; Reffold *et al.* 2008; UKWIR 2008; Crawford *et al.* 2011; Johnston 2011; Corominas *et al.* 2012; Goel *et al.* 2012; Tampa Bay Water 2012; EnviroSim Associates Ltd 2014). These studies provide designers, managers, and researchers with useful information; however, further research is needed to understand the major trends of carbon footprint of water reuse and desalination systems and current state of available tools for estimating the carbon footprint of these systems.

Therefore, the goal of this review is to identify the needs for future research and practice that could facilitate accurate carbon footprint estimations of water reuse and desalination systems. Previous studies were compared to identify challenges, trends, and major factors impacting the carbon footprint and GHG emissions of water reuse and desalination systems. Additionally, carbon footprint estimation tools were reviewed to identify limitations, challenges, and knowledge gaps. Lastly, recommendations are provided to support the development of a more accurate and applicable carbon footprint estimation tool for water reuse and desalination systems.

THE CHALLENGE OF CARBON FOOTPRINT COMPARISONS

Based on limited data available in the literature, the estimated carbon footprint associated with RO desalination ranges from 0.4 to 6.7 kg CO_2eq/m^3, whereas water reuse systems range from 0.1 to 2.4 kg CO_2eq/m^3. These wide variations in range can be largely attributed to impacting factors including: location, technologies evaluated, life cycle stages considered, parameters considered, estimation methodologies, and the overall lack of representative studies that consider carbon footprint. Table 1 highlights the wide variation in these major impacting factors from representative studies.

Location has a large impact on site-specific conditions of water reuse and desalination systems such as electricity mix, water quality, and geographical conditions, leading to changes in carbon footprint estimations. For example, various studies showed that the electricity mix used for energy production has a large impact on Scope 2 emissions (Raluy *et al.* 2004, 2005a, b; Ortiz *et al.* 2007; Biswas 2009; Stokes & Horvath 2009). Similarly, influent water quality (e.g. brackish groundwater versus seawater) and intended level of treatment (e.g. potable versus non-potable) influence technology selection and associated energy consumption (Fine & Hadas 2012; Peters & Rouse 2005; Stokes & Horvath 2006; Lyons *et al.* 2009).

Geographical conditions can also impact the carbon footprint of water reuse and desalination systems. Seawater is often treated using RO technologies, which is then distributed to end-users through an existing potable water distribution system. Conversely, wastewater has traditionally been transported through gravity sewers to a centralized wastewater treatment plant (WWTP) (Stokes & Horvath 2006; Lee *et al.* 2013). After treatment, high pumping energy is required to transfer water back to end-users through separate distribution infrastructure, increasing the carbon footprint associated with energy consumption (Scope 2) and construction materials (Scope 3). As a

Table 1 | Summary of representative literature evaluating the carbon footprint of water reuse and desalination systems

Study	Location	Facility	Technologies/processes	Life stages	Parameters considered	Methodology
Raluy *et al.* (2004)	Spain	Desalination	MED, MSF, RO	CLS, O&M, DLS	Materials, delivery, electricity, demolition, disposal	PLCA
Raluy *et al.* (2005a)	Spain	Desalination	MED, MSF, RO	O&M	Electricity	PLCA
Raluy *et al.* (2005b)	Spain	Desalination	RO	CLS, O&M, DLS	Fuel, materials, electricity, demolition, disposal	PLCA
Muñoz & Fernández-Alba (2008)	Spain	Desalination	RO	CLS, O&M, DLS	Fuel, materials, delivery, electricity, chemicals, demolition, transport of waste, disposal	PLCA
Biswas (2009)	Australia	Desalination	RO	O&M	Electricity, chemicals, replacement materials	PLCA
Shrestha *et al.* (2011)	United States	Desalination	Seawater desalination	O&M	Electricity	Electricity and EF
Jijakli *et al.* (2011)	UAE	Desalination	RO, Solar Still	CLS, O&M, DLS	Fuel, materials, electricity, demolition	PLCA
Tangsubkul *et al.* (2005)	Australia	Water reuse	CAS with membrane treatment, MBR-RO, waste stabilization ponds	CLS, O&M	Fuel, materials, electricity, chemicals, direct emissions	PLCA, EIO-LCA
Ortiz *et al.* (2007)	Spain	Water reuse	CAS-Immersed MBR, CAS-External MBR, CAS-Filtration	CLS, O&M, DLS	Materials, delivery, electricity	PLCA
Friedrich *et al.* (2009)	South Africa	Water reuse	Collection, primary treatment, CAS, flocculation, coagulation, filtration, ozonation, GAC, chlorination	CLS, O&M	Fuel, materials, electricity, chemicals, potable water offsets	PLCA
Stillwell & Webber (2010)	United States	Water reuse	Various (e.g. trickling filters, CAS)	O&M	Electricity, avoided potable water use	Electricity and EF
Fine & Hadas (2012)	Israel	Water reuse	Secondary aeration with nitrification/denitrification, clarifiers and deep sand filtration	O&M	Electricity, direct emissions, nutrient offsets, energy offsets	COD, energy and EF
Mo & Zhang (2012)	United States	Water reuse	Primary and secondary treatment, nitrogen removal, post-aeration, and chlorine disinfection	CLS, O&M	Materials, electricity, water offsets, nutrient offsets, energy offsets	EIO-LCA and EF
Cornejo *et al.* (2013)	Bolivia	Water reuse	Bathrooms, collection, 3-Pond and UASB-Pond Systems	CLS, O&M	Fuel, materials, delivery, electricity, direct emissions, energy offsets, water offsets	PLCA
Lundie *et al.* (2004)	Australia	Both	Filtration, distribution, use, WWTPs, biosolids reuse	CLS, O&M	Materials, electricity, chemicals, transportation, energy offsets, nutrient offsets	PLCA

(*continued*)

Table 1 | continued

Study	Location	Facility	Technologies/processes	Life stages	Parameters considered	Methodology
Stokes & Horvath (2006)	United States	Both	RO versus coagulation, filtration, disinfection	CLS, O&M	Fuel, materials, delivery, electricity, equipment, chemicals	PLCA
Lyons *et al.* (2009)	United States	Both	RO versus MF/RO, aquifer storage and recovery	CLS, O&M	Materials, electricity, chemicals	PLCA
Muñoz *et al.* (2009)	Spain	Both	Ozonation (with and without hydrogen peroxide) replacing seawater desalination	O&M	Electricity, chemicals, delivery	PLCA
Pasqualino *et al.* (2010)	Spain	Both	Collection, grit removal, clarifiers, coagulation, flocculation, filtration, chlorination, and UV replacing desalination	O&M	Materials, delivery, electricity, potable water offsets, desalinated water offsets	PLCA
Stokes & Horvath (2009)	United States	Both	RO versus filtration and disinfection	CLS, O&M	Fuel, materials, delivery, electricity, equipment, chemicals	PLCA and EIO-LCA
Meneses *et al.* (2010)	Spain	Both	Chlorination and UV treatment, ozonation, ozonation and hydrogen peroxide, desalination	O&M	Electricity, chemicals, transport of waste, disposal, potable water offsets	PLCA
Muñoz *et al.* (2010)	Spain	Both	RO, UV and membranes	CLS, O&M, DLS	Materials, electricity, chemicals	PLCA
de Haas *et al.* (2011)	Australia	Both	RO and WWTPs producing different water quality	CLS, O&M	Electricity, chemicals, direct emissions, energy offsets, nutrient offsets, potable water offsets	PLCA

CLS – Construction life stage; CAS – Conventional activated sludge; COD – Chemical oxygen demand; DLS – Decommission life stage; EF – Emission factor; EIO-LCA – Environmental input/output life cycle assessment; GAC – Granular activated carbon; MBR – Membrane bioreactor; MF – Microfiltration; MED – Multi-effect distillation; MSF – Multi-stage flash; O&M – Operation and maintenance; PLCA – Process life cycle assessment; RO – Reverse osmosis; UASB – Upflow anaerobic sludge blanket reactor; UV – Ultraviolet; WWTP – Wastewater treatment plant.

result, the estimated carbon footprint is highly dependent on site-specific conditions.

Other factors that impact the carbon footprint estimations include life stages and parameters considered in calculations. All studies reviewed include the operation and maintenance (O&M) stage, but less than half consider the construction stage. Additionally, almost all studies include on-site energy usage during O&M that contribute to Scope 2 emissions. However, fewer studies consider the relative contributions from direct process emissions (e.g. CH_4 and N_2O) of water reuse systems (Tangsubkul *et al.* 2005; Foley *et al.* 2010; de Haas *et al.* 2011; Fine & Hadas 2012; Cornejo *et al.* 2013). Consequently, comparing the carbon footprint of systems across different studies poses a challenge when different life cycle stages and parameters are considered.

Another major challenge to ensuring fair comparisons is from the variations in methodology and estimation tools used to analyze the carbon footprint. More information on carbon footprint estimation tools for water reuse and desalination is provided in a previous publication (Mihelcic *et al.* 2013). Most of the previous studies used life cycle assessment (LCA), which often includes supply-chain emissions (Scope 3) associated with material and chemical production (ISO 2006). A disadvantage of LCA is that the selection of system boundaries changes with the goal and scope of a study, which can lead to difficulties in comparing results.

CARBON FOOTPRINT TRENDS

Despite the challenges to compare the carbon footprint from various studies, the carbon footprint of desalination systems was generally found to be higher than water reuse systems (Lundie *et al.* 2004; Stokes & Horvath 2006, 2009; Lyons *et al.* 2009; Muñoz *et al.* 2009; de Haas *et al.* 2011). For example, Stokes & Horvath (2006) found that seawater desalination with flocculation, filtration, RO, and disinfection had a carbon footprint three times greater than water reclamation with coagulation, filtration, and disinfection. In this study, seawater is treated to potable standards while reclaimed water is treated to replace potable water used for irrigation and other non-potable reuse applications. Another study found that the carbon footprint of certain tertiary technologies for water reuse (e.g. ozone or ozone peroxide) was 85% less than seawater RO desalination (Muñoz *et al.* 2009). Expanding on the work of Muñoz *et al.* (2009), Meneses *et al.* (2010) found that the carbon footprint of UV and chlorination disinfection options for water reuse were comparable to ozone and ozone peroxide.

Table 2 | CO_2 emissions per m^3 of produced water for different desalination technologies

Technology	CO_2 emissions (kg CO_2/m^3)	Total electrical energy (kWh/m^3)[a]
MED	0.3–26.9	6.0–10
MSF	0.3–34.7	13.5–23.5
RO	0.08–4.3	4.0–4.5

[a] Total electrical energy data from Erdal *et al.* (2012). *Sources:* Raluy *et al.* (2004, 2005a, 2006); Peters & Rouse (2005); Biswas (2009); Lyons *et al.* (2009); Jijakli *et al.* (2011).

Trends of carbon footprint of desalination

Reverse osmosis technologies were reported to have significantly lower CO_2 emissions than thermal technologies (e.g. multi-effect distillation (MED), multi-stage flash (MSF)) for an equivalent volume of water produced under similar electricity mixes (see Table 2). This is largely because the energy required for the high pressure pump needed to overcome osmotic pressure in RO systems (4.0–4.5 kWh/m^3) is lower than the energy required to provide heat for thermal technologies (6.0–23.5 kWh/m^3) (Raluy *et al.* 2004; Erdal *et al.* 2012). Further efforts to reduce RO electricity consumption can be achieved through energy recovery devices, which have reduced energy usage at a brackish RO treatment facility in Port St. Lucie, Florida by 25% (Littrell *et al.* 2012) and are gaining acceptance in the industry. Electricity consumption is typically the largest contributor to the carbon footprint of these systems; however, indirect emissions from chemical and material production were also found to be important contributors (Stokes & Horvath 2006; Lyons *et al.* 2009; de Haas *et al.* 2011).

For RO desalination, factors that impact the carbon footprint include influent levels of total dissolved solids (TDS), pretreatment technology selection, and electricity mix. Influent TDS levels for seawater desalination are on the order of 35,000 mg/L compared to 1,000–15,000 mg/L for brackish water, with seawater desalination also requiring a higher level of pretreatment. Table 3 highlights that brackish water desalination typically yields a lower carbon footprint than seawater desalination (Peters & Rouse 2005; Stokes & Horvath 2006, 2009; Muñoz & Fernández-Alba 2008)

Table 3 | Carbon footprint of RO desalination technologies for seawater and brackish water

Treatment type	Influent TDS (mg/L)	Pretreatment	Carbon footprint (kg CO_2eq/m^3)	Remarks
Seawater RO (SWRO)	30,000–40,000	Not specified Conventional Media Filtration Membrane	1.9–6.7 2.3–2.5 0.4–4.0	Conventional pretreatment has lower emissions than membrane filtration for comparable electricity mixes. Lower end of range from all solar thermal generation or all wind. Upper end of range from national grid electricity mixes
Brackish water RO (BWRO)	1,000–15,000	Either	0.4–2.5	Brackish groundwater and brackish surface water desalination yields lower GHG emissions than seawater desalination due to lower levels of electricity needed to treat lower levels of TDS

Sources: Peters & Rouse (2005); Stokes & Horvath (2006, 2009); Muñoz & Fernández-Alba (2008); Biswas (2009); Muñoz *et al.* (2009); Beery *et al.* (2010); de Haas *et al.* (2011).

because it requires a lower level of salt rejection to meet water quality objectives. Furthermore, the carbon footprint of RO systems with membrane pretreatment (e.g. ultrafiltration) is generally higher than RO systems with conventional pretreatment systems (e.g. granular media filtration) for seawater desalination. One reason in the case of seawater desalination is because the membranes may require addition of coagulant upstream of the membranes and frequent chemical cleanings, steps that increase the carbon footprint.

Trends of carbon footprint of water reuse

Similar to desalination, most water reuse studies (Stokes & Horvath 2006; Ortiz *et al.* 2007; Friedrich *et al.* 2009; Lyons *et al.* 2009; Pasqualino *et al.* 2010; de Haas *et al.* 2011) found that energy consumption is a dominant factor contributing approximately 68–92% of the carbon footprint (Tangsubkul *et al.* 2005; Stokes & Horvath 2009). Many studies confirmed that aeration using conventional activated sludge (CAS) led to high electricity consumption (Friedrich *et al.* 2009; Pasqualino *et al.* 2010; Zhang *et al.* 2010) and consequently high Scope 2 emissions during the operation phase, as expected. Conversely, methane emissions were also found to be a dominant contributor (~58–69%) to the carbon footprint of systems that implement waste stabilization ponds (Tangsubkul *et al.* 2005; Cornejo *et al.* 2013), highlighting the importance of direct emissions (Scope 1).

Generally, the carbon footprint of secondary treatment is higher than the carbon footprint of tertiary treatment using filtration and disinfection processes. For example, Friedrich *et al.* (2009) found that CAS contributed three times more CO_2 than a tertiary treatment train (e.g. coagulation, sand/anthracite filtration, ozonation, granular activated carbon (GAC), and chlorination), where 90% of the CO_2 emissions were associated with electricity consumption. In another study, Pasqualino *et al.* (2010) found that the carbon footprint of primary, secondary and sludge treatment (0.83 kg CO_2eq/m^3) was higher than a tertiary treatment train including coagulation, flocculation, chlorination, sand filtration, and UV disinfection (0.16 kg CO_2eq/m^3).

Level of treatment has also been found to impact the carbon footprint results of previous studies (Foley *et al.* 2010). Table 4 highlights this trend, in which the carbon footprint increases as treatment level increases for varying end-use applications. Consequently, secondary and tertiary treatment suitable for indirect potable reuse has a higher carbon footprint than secondary treatment suitable for non-food crop irrigation, as expected.

Limited research has been conducted on the carbon footprint of technologies used to achieve specific trace constituent removal for direct potable reuse (Leverenz *et al.* 2011). However, Sobhani & Rosso (2011) studied the contribution of an advanced oxidation process (AOP) in treating *N*-nitrosodimethylamine, a possible cancer-causing agent, to the overall energy and carbon footprints of the indirect potable reuse system in Orange County, California. It was estimated that influent pumping, primary treatment,

Table 4 | Carbon footprint and carbon dioxide emissions per m^3 of produced water for water reuse systems at different treatment levels

End-Use	Recommended treatment level	Carbon footprint (kg CO_2eq/m^3)	Carbon dioxide emissions (kg CO_2/m^3)	Remarks
No use recommended	Primary	0.11–0.16	–	Primary treatment is generally lower than secondary and tertiary treatment
Non-food crop irrigation[a]	Secondary	0.30–2.0	0.13–0.69	For CO_2 emissions, low point from Norwegian electricity mix, high value from average European electricity mix, average airborne emissions
Indirect potable reuse[b]	Secondary and tertiary	0.6–2.4	0.14–0.98	For carbon footprint, low value is for demand-driven advanced treatment and high value is advanced treatment for 100% of the wastewater effluent

[a] Includes restricted landscape irrigation, surface irrigation of orchards and vineyards, groundwater recharge of non-potable aquifer, stream augmentation, and industrial cooling (Mo & Zhang 2013).

[b] Includes landscape irrigation, urban reuse, food crop irrigation, and indirect potable reuse (Mo & Zhang 2013). *Sources:* Lundie *et al.* (2004); Tangsubkul *et al.* (2005); Ortiz *et al.* (2007); Friedrich *et al.* (2009); Lyons *et al.* (2009); Pasqualino *et al.* (2010); de Haas *et al.* (2011); Fine & Hadas (2012); Mo & Zhang (2012); Cornejo *et al.* (2013).

secondary treatment, micro-filtration, AOP, and RO contributed 3, 4, 16, 21, 7, and 49% of the total energy footprint, respectively. This suggests that RO and AOP contribute to about half of the total energy consumption. Additionally, the study highlighted that there is a difference between technologies required for non-potable reuse (e.g. landscaping and irrigation) as opposed to potable reuse, which typically involves advanced treatment including RO and AOP.

Some studies incorporate benefits associated with resource recovery as a credit in the carbon footprint estimation (Lundie *et al.* 2004; Meneses *et al.* 2010; Pasqualino *et al.* 2010; Stillwell & Webber 2010; Fine & Hadas 2012; Mo & Zhang 2012). These benefits provide potential carbon footprint offsets through water reclamation (e.g. offsets energy used to treat potable water), nutrient recovery (e.g. offsets synthetic fertilizers), and energy recovery (e.g. offsets electricity from grid). For example, Mo & Zhang (2012) found that reclaiming water from the Howard Curren WWTP in Tampa could offset 36–40% of the total carbon footprint. Where treating water to a higher level requires more energy and resource inputs, the carbon footprint offset potential of reclaimed water increases with higher-value end uses (e.g. replacing high-purity water for industrial processes has a higher offset potential than agricultural reuse) (Pasqualino *et al.* 2010; Tong *et al.* 2013).

CARBON FOOTPRINT ESTIMATION TOOLS FOR WATER REUSE AND DESALINATION

Availability and applicability

Sixteen available emission tools with varying levels of applicability to water reuse and desalination were reviewed. Table 5 highlights the tool type (e.g. software, MS-Excel, web-based), availability (e.g. commercial, public, upon request), and source of the various tools. The different tools may be classified as (1) process LCA tools, (2) hybrid LCA tools, (3) specific tools, and (4) other related tools. Eight out of the 16 available tools are software-based, six are MS-Excel spreadsheets, and two are web-based. Additionally, eight out of the 16 tools are commercially sold, five are available on request, and three are publicly available online. Further details on system boundaries, data sources, input parameters, calculation methods, output parameters, limitations, and applicability of these tools is available elsewhere (Mihelcic *et al.* 2013).

The application of process LCA tools varies widely, spanning a range of products and processes. This limits their applicability to carbon footprint estimations specific to water reuse and desalination. In contrast, hybrid LCA tools and the UK Environment Agency tool were specifically designed to estimate the carbon footprint of water, water reuse and desalination facilities. The hybrid LCA tools are specific to facilities in the USA, whereas the UK Environment Agency tool is specific to facilities in the UK. Specific tools (e.g. Tampa Bay Water and Johnston tools) and the Carbon Accounting Workbook (UK) are applicable to water facilities. However, the Tampa Bay Water tool is also applicable to desalination facilities and the Johnston tool contains some disinfection and desalination processes that could be useful for estimating the carbon footprint of water reuse or desalination facilities. The remaining tools are applicable to wastewater treatment facilities and, therefore, contain attributes that are useful for estimating the carbon footprint of water reuse facilities. The following sections compare hybrid LCA and specific tools while discussing key attributes from other related tools that could be integrated into a single tool to facilitate accurate and consistent estimations.

KNOWLEDGE GAPS, LIMITATIONS, AND CHALLENGES OF CARBON FOOTPRINT ESTIMATION

Table 6 summarizes knowledge gaps and key challenges associated with carbon footprint estimation tools for water reuse and desalination systems. Further research in these critical areas is needed to develop a comprehensive tool that enables accurate estimations.

Life stages and parameters considered

Differences in carbon footprint results arise from differences in specific life stages, parameters, and system boundaries considered in the carbon footprint estimation tools. Table 7 shows a summary of parameters considered by

Table 5 | Description of available carbon footprint estimation tools related to water reuse or desalination

Type	Description of methodology	Estimation tool	Tool format	Available	Applicable	Source
Process LCA-based tools	Use process-based inventory over life cycle[a]	SimaPro	Software	Commercial	Varies, any product or process	http://www.pre.nl
		Gabi	Software	Commercial		http://www.gabi-software.com
		SiSOSTAQUA	Software	Commercial		http://www.simpple.com
Hybrid LCA-based tools	Use both process-based and input-output based inventory over life cycle[b]	WEST	MS-Excel	Upon request	Water, water reuse, desalination	Dr Jennifer Stokes at ucbwaterlca@gmail.com
		WWEST	MS-Excel	Upon request	Wastewater	Dr Jennifer Stokes at ucbwaterlca@gmail.com
		WESTWeb	Web-based	Public	Water, water reuse, desalination, wastewater	west.berkeley.edu
Specific tools	Uses input parameters specific to utility over O&M	Tampa Bay Water[c]	MS-Excel	Upon request	Water and desalination	http://www.tampabaywater.org
		Johnston Tool[d]	MS-Excel	Upon request	Water	Dr Tanju Karafil at tkaranf@clemson.edu
Other related tools	NOT specifically used to estimate emissions from water reuse or desalination facilities, but contain aspects that are applicable	CHEApet[e]	Web-based	Public	Wastewater	cheapet.werf.org
		UK Environment Agency tool[f]	MS-Excel	Upon request	Water supply, water reuse, desalination	Environment Agency at enquiries@environment-agency.gov.uk
		Bridle and BSM2G tool[g]	Software	Public	Wastewater	Dr Lluis Corominas at lcorominas@icra.cat
		System Dynamics[h]	Software	Commercial	Varies	http://www.iseesystems.com
		GPS-X[i]	Software	Commercial	Wastewater	http://www.hydromantis.com/GPS-X.html
		Carbon Accounting Workbook, 5th version[j]	MS-Excel	Commercial	Water	http://www.ukwir.org
		mCO2[k]	Software	Commercial	Wastewater	http://www.mwhglobal.com
		BioWin 4.0[l]	Software	Commercial	Wastewater	http://www.envirosim.com

[a] ISO (2006).
[b] Stokes & Horvath (2006, 2011a, b).
[c] Tampa Bay Water (2012).
[d] Johnston (2011).
[e] Crawford *et al*. (2011).
[f] Reffold *et al*. (2008).
[g] Corominas *et al*. (2012).
[h] Shrestha *et al*. (2011).
[i] Goel *et al*. (2012).
[j] UKWIR (2008).
[k] MWH (2012).
[l] EnviroSim Associates Ltd (2014).

hybrid LCA tools and specific tools. This table highlights that the carbon footprint from operational electricity consumption and the associated electricity mix are the only parameters considered by both hybrid LCA and specific tools.

Although operational electricity consumption was found to be a dominant contributor to the carbon footprint in previous studies (Ortiz *et al*. 2007; Friedrich *et al*. 2009), other emission sources can also be important. The hybrid LCA tools allow users to estimate impacts associated with

Table 6 | Knowledge gaps, limitations, and challenges for water reuse and desalination carbon footprint estimation tools

Tool aspect	Knowledge gaps/limitations/key challenges
Parameters and life stages considered	Knowledge gap: Contribution of direct emissions for water reuse. Knowledge gap: Emissions of membranes production, renewal and disposal and brine disposal. Knowledge gap: Appropriate allocation methods to account for resource recovery. Key challenge: Reaching consensus on the appropriate parameters and life stages to consider.
Input data	Limitation: Availability of input data for existing tools. Key challenge: Develop model with enough detailed data to determine critical areas for GHG mitigation.
Output data	Limitation: Lack of separation of carbon footprint by unit process. Limitation: Lack of separation of carbon footprint by scope 1, 2, and 3 emissions. Key challenge: Conducting comparable estimations for each unit process.
Additional useful attributes	Limitation: User-friendly, regionally transferable tool widely used Limitation: Methods for model calibration, validation and/or sensitivity analysis embedded in tool. Key challenge: Integration of robust and accurate tool, which combines beneficial attributes.

construction and O&M stages, whereas specific tools focus solely on the operational life stage. Despite the dominance of operation phase emissions, studies investigating natural wastewater treatment technologies (e.g. waste stabilization ponds) found that the construction phase was important, contributing 25–42% to the carbon footprint (Tangsubkul *et al.* 2005; Cornejo *et al.* 2013).

The Johnston tool and hybrid LCA tools consider a more complete set of parameters (e.g. fuel consumption, chemical production, sludge disposal, direct emissions, and process-specific emissions). For example, the wastewater energy sustainability tool (WWEST) and water energy sustainability tool web version (WESTWeb) can estimate direct process emissions (e.g. CH_4 and N_2O) from various wastewater treatment processes based on water quality data and population served. Direct process emissions could be important for carbon footprint mitigation efforts since they can be directly controlled through process modifications (Stokes & Horvath 2010; de Haas *et al.* 2011). Further research is needed to quantify the direct process emissions (e.g. fugitive CH_4 and N_2O) and the carbon footprint reduction due to control technologies.

The Johnston tool, WWEST, and WESTWeb also include some process-specific carbon footprint estimates from relevant materials and equipment (e.g. filter media, membranes, and blowers). This enables the identification of carbon intensive processes, which can enhance mitigation efforts. However, further investigation is needed to determine the appropriate life stages and parameters to include in a carbon footprint analysis of water reuse and desalination facilities.

Input data

A major difference between the hybrid LCA tools and the specific tools is the amount of input data required for a comprehensive analysis. A large amount of data is required to conduct a comprehensive analysis using hybrid LCA tools. Users are not required to enter all of the inputs; however, the arbitrary selection of default data inputs could lead to inaccurate estimations. Additionally, some water reuse and desalination facilities may not have or collect sufficient input data required by the hybrid LCA tools (Mihelcic *et al.* 2013). The lack of input data collected in practice is thus a limitation to the successful implementation of the hybrid LCA tools.

In contrast, the specific tools require fewer inputs than the hybrid LCA tools, since they focus only on emissions associated with the operational life stage. Fewer inputs could be beneficial to facilitate widespread adoption and provide water utility decision makers an easy-to-use tool for evaluation of carbon footprint.

To evaluate the differences of available tools, two were compared using data from a previous study (Stokes & Horvath 2009). The Tampa Bay Water tool represents the simplest available tool requiring minimal data inputs (e.g. electricity consumption, electricity mix), whereas WESTWeb represents a more sophisticated tool requiring

Table 7 | Parameters considered by hybrid LCA and specific tools that contribute to the carbon footprint. *X* = included

	Hybrid LCA tools			Specific tools	
Parameters considered	**WEST**[a]	**WWEST**[a]	**WESTWeb**[a]	**Johnston tool**[b]	**Tampa Bay Water tool**[c]
Material production	X	X	X		
Material delivery	X	X			
Electricity consumption	X	X	X	X	X
Electricity mix	X	X	X	X	X
Fuel use (on-site and fleet vehicles)	X	X	X	X	
Sludge disposal	X	X	X	X[d]	
Chemical production	X	X	X	X	
Direct process emissions		X[e]	X[e]	X[d]	
Process equipment	X[f]	X[f]	X[f]	X[g]	
Disinfection processes	X[f]	X[f]	X[f]	X[g]	

[a] Johnston (2011).
[b] Stokes & Horvath (2011a, b).
[c] Tampa Bay Water (2012).
[d] Direct emission factors for ozone generation, GAC, reservoirs, and sludge disposal from potable water production, not applicable to water reuse or desalination.
[e] Direct emission for various wastewater treatment processes.
[f] Includes filter media (sand, gravel, anthracite, or other coal product), membranes, pumps, fans/blowers, motors and generators, turbines, metal tanks, UV lamps/lights, other industrial equipment, electrical, and controls.
[g] Utilities can estimate energy consumption from mixers, flocculators, settlers, DAF, filtration, MF/UF, UV, ozone, hypochlorite, decarbonators, RO, and thermal desalination by entering the average flow rate.

extensive data inputs (e.g. material production, chemical usage, fuel usage, electricity consumption, electricity mix).

Figure 1 shows the estimated carbon footprint for three different facilities assessed (capacity of 26.1 mgd): a seawater desalination facility, a brackish groundwater desalination facility, and a water reuse facility. These estimations fall within ranges reported previously for seawater RO desalination, brackish water RO desalination, and water reuse. Figure 1 highlights that the carbon footprint per m^3 of produced water from the Tampa Bay water tool accounts for 55–58% of the WESTWeb estimate. The difference in estimations demonstrates that the Tampa Bay Water tool underestimates life cycle impacts included in the more comprehensive hybrid LCA tool.

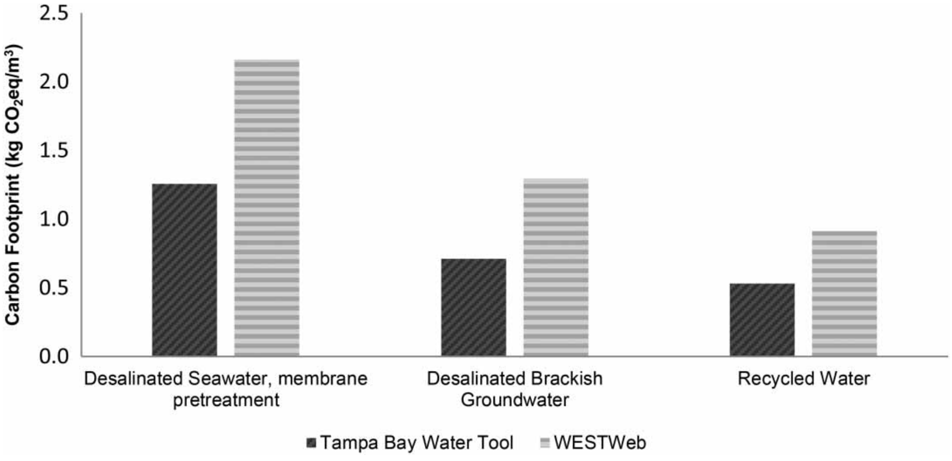

Figure 1 | Comparison of carbon footprint estimate using Tampa Bay Water and WESTWeb tools.

Output data

Many existing tools do not separate carbon footprint results by unit processes. For example, both hybrid LCA and specific tools are currently not set up to distinguish between the carbon footprint contributions from primary, secondary, and tertiary treatment steps. The separation of carbon footprint and GHG emissions associated with specific unit processes would allow utilities to identify high impact areas. Determining the contribution of specific treatment steps may require energy estimations for each unit process since this data is often not collected in practice. Energy estimation equations have been developed for some water and wastewater unit processes and should be validated using actual energy consumption data (Carlson & Walburger 2007; Johnston 2011).

Another limitation for most tools is the lack of separation between Scope 1, 2, and 3 carbon footprint results. The Tampa Bay water tool, for example, only presents Scope 2 results from electricity consumption, whereas the hybrid LCA tools present all Scope 1, 2, and 3 results collectively. The Johnston tool presents carbon footprint results as Scope 1 (direct), Scope 2 (indirect), and Scope 3 (other indirect) emissions for water treatment estimates, but this tool is not specific to water reuse and desalination facilities. The separation of results as Scope 1, 2, and 3 emissions would be beneficial, as this is consistent with published protocols (e.g. Local Government Operations Protocol and WRI/WBCSD GHG Protocol Corporate Standard). Existing and voluntary carbon footprint reporting programs include Scopes 1 and 2 emissions, as will future regulations or cap-and-trade programs (Huxley *et al.* 2009).

RECOMMENDATIONS FOR CARBON FOOTPRINT ESTIMATION TOOL

Efforts to collect input data should increase to obtain enough detailed data to determine critical areas for carbon footprint mitigation. A robust carbon footprint estimation tool would provide separate results by both emission scope and unit process. Quantification and separation of direct (Scope 1) and indirect (Scopes 2 and 3) emissions would enable comparisons between facilities.

Regionally transferable attributes are also important to increase adoption of carbon footprint estimation tools. For example, the Johnston tool and hybrid LCA tools contain regionally transferable electricity mixes, which allows users to select a custom, state, or national electricity grid for the USA through the embedded eGRID (Emissions and Generation Resource Integrated Database) data (EPA 2013).

Additionally, some key attributes from other related tools would be beneficial to include in a single robust carbon footprint estimation tool for water reuse and desalination facilities. Key attributes include: (1) a user-friendly web-based interface, (2) a dynamic model that captures how GHG emissions respond to operational changes, (3) carbon footprint offset potential associated with resource recovery, and (4) model calibration and validation (see Table 8).

Some wastewater carbon footprint estimation tools (e.g. carbon heat energy analysis plant evaluation tool (CHEApet) and mCO_2) contain user-friendly interfaces. Similar to WESTWeb, CHEApet provides a web-based interface, whereas mCO_2 software automatically produces a report to identify critical mitigation areas (Crawford *et al.* 2011; MWH 2012). These examples of user-friendly attributes could lead to greater adoption in both research and practice.

A robust estimation tool should also contain dynamic quantifications of how operational changes impact results. To capture the impact of operational changes, the Benchmark Simulation Model Platform No. 2 (BSM2G) includes a dynamic process-based GHG estimation tool that can analyze how changes in the system (e.g. hydraulic load, influent water quality, temperature, and operational modifications) impact direct N_2O and CH_4 emissions from secondary treatment (i.e. activated sludge) and sludge processing (i.e. anaerobic digestion) (Corominas *et al.* 2012).

Accounting for the offsets associated with resource recovery would also be beneficial to practitioners and researchers. The GPS-X tool includes offsets due to the recovery of energy, fertilizers, and carbon sequestration from land use (Goel *et al.* 2012), whereas WWEST includes offsets associated with energy and fertilizer co-products (Stokes & Horvath 2011a). No tool reviewed incorporated the offset potential of water reuse for varying applications and end-uses.

Table 8 | Useful attributes from other related carbon footprint tools for wastewater that would be beneficial to a carbon footprint estimation tool for water reuse or desalination systems

Estimation tool	Useful attributes	Benefit of attribute
CHEApet[a]	User-friendly web-based tool containing some tertiary filtration and UV disinfection estimation capabilities. Future versions will include biological and chemical phosphorus removal, step-feed BNR, and chlorine disinfection estimation abilities, which would be useful to making a more robust tool	The web-based interface is beneficial to user-friendliness, while process-specific estimation capabilities can increase transferability of technology comparisons
BSM2G[b]	A dynamic process-based tool that captures variations in operating conditions, temperature, and influent loads over time	Dynamic modeling desalination unit processes or tertiary treatment processes for water reuse could be beneficial to a robust tool
GPS-X[c]	Future version of GPS-X will include offsets due to fertilizers and carbon sequestration from land use. Additionally, it can be used to evaluate how process changes affect emissions. The GPS-X model was also tested against carbon footprint data from a wastewater treatment facility to calibrate and validate the accuracy of results	This is the only tool that used calibration and validation to verify results, which would be useful to the development of a robust water reuse carbon footprint estimation tool
mCO2[d]	User-friendly software that automatically produces a report identifying critical areas to meet emission criteria	User-friendly software is a crucial element to the successful development of a carbon footprint tool for water reuse or desalination systems

[a] Crawford *et al.* (2011).
[b] Corominas *et al.* (2012).
[c] Goel *et al.* (2012).
[d] MWH (2012).

Model validation is important to ensure the accuracy of carbon footprint estimates. For example, carbon footprint estimates from the GPS-X tool were calibrated to match actual data (Goel *et al.* 2012). Estimates of direct emissions can be validated through comparisons to GHG emissions monitored on-site.

SUMMARY

The goal of this study was to identify the needs for future research and practice to facilitate accurate carbon footprint estimations for water reuse and desalination utilities through a critical review of literature and estimation tools. Variations in location, technology, life cycle stages, parameters considered, and carbon footprint estimation tools present challenges to compare results from different studies. Despite these challenges, it was determined that the estimated carbon footprint of seawater RO desalination is generally larger than brackish water RO desalination and water reuse. Future tools should allow for different levels of sophistication for input data, but provide enough detail to determine critical mitigation areas. The separation of direct and indirect emissions, as well as the separation of unit processes contributions from primary, secondary, and tertiary treatment steps and proper resource recovery allocation would provide decision makers a greater ability to make choices that consider carbon footprint in the analysis of alternatives.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the WateReuse Research Foundation's financial, technical, and administrative assistance in funding and managing the project through which this information was discovered (Project no. 10-12). The authors also acknowledge utilities that participated in the study including Tampa Bay Water, Miami-Dade Water and Sewer Department, Palm Beach County Water Utilities, City of Tampa Howard F. Curren

Advanced Wastewater Treatment Plant and San Elijo Joint Powers Authority in Cardiff by the Sea, California. This material is also based in part upon work supported by the National Science Foundation under Grant Number HRD#1139850. P.K. Cornejo was supported by the NSF FGLSAMP Bridge to the Doctorate Award, McKnight Doctoral Fellowship, and Sloan Minority PhD program. M.V.E Santana was supported by the Department of Education Graduate Assistance in Areas of National Need Fellowship program.

REFERENCES

Beery, M., Wozny, G., Repke, J., Pierucci, S. & Buzzi-Ferraris, G. 2010 Sustainable design of different seawater reverse osmosis desalination pretreatment processes. *Comput. Aided Chem. Eng.* **28**, 1069–1074.

Biswas, W. K. 2009 Life cycle assessment of seawater desalination in Western Australia. *World Acad. Sci. Eng. Tech.* **56**, 369–375.

Carlson, S. & Walburger, A. 2007 Energy Index Development for Benchmarking Water and Wastewater Utilities. Report of the AWWA Research Foundation. AWWA Research Foundation, Albany, NY.

Cornejo, P. K., Zhang, Q. & Mihelcic, J. R. 2013 Quantifying benefits of resource recovery from sanitation provision in a developing world setting. *J. Environ. Manage.* **131**, 7–15.

Corominas, L., Flores-Alsina, X., Snip, L. & Vanrolleghem, P. A. 2012 Comparison of different modeling approaches to better evaluate greenhouse gas emissions from whole wastewater treatment plants. *Biotechnol. Bioeng.* **109**, 2854–2863.

Crawford, G., Johnson, T. D., Johnson, B. R., Krause, T. & Wilner, H. 2011 CHEApet User's Manual. Report of the Water Environment Research Foundation. Water Envirnoment Federation, Alexandria, VA.

de Haas, D., Lane, J. & Lant, P. 2011 Life cycle assessment of the Gold Coast urban water system: achieving a balance between opposing environmental impacts is a challenge. *Water* **38**, 57–64.

EPA 2013 Emissions and generation resource integrated database (eGRIDweb). Retrieved 1 November 2013. Available from: http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html.

Erdal, U. G., Lozier, J. & Bergman, R. 2012 Innovative and developmental desalination technologies – how mature they are? Paper presented at the 27th Annual WateReuse Symposium, Hollywood, Florida.

EnviroSim Associates Ltd 2014 New development in BioWin 4.0. Retrieved February 10, 2014. Available from: http://www.envirosim.com/files/downloads/WhatsNew40.pdf.

Fine, P. & Hadas, E. 2012 Options to reduce greenhouse gas emissions during wastewater treatment for agricultural use. *Sci. Total Environ.* **416**, 289–299.

Foley, J., de Haas, D., Hartley, K. & Lant, P. 2010 Comprehensive life cycle inventories of alternative wastewater treatment systems. *Water Res.* **44**, 1654–1666.

Foster, J., Uhlig, A. D., Cutler, D., Reed, A., Wong, T. & Hamilton, L. 2013 *Seattle Climate Action Plan*. Report of the Seattle City Council. Seattle City Council, Seattle, Washington.

Friedrich, E., Pillay, S. & Buckley, C. A. 2009 Carbon footprint analysis for increasing water supply and sanitation in South Africa: a case study. *J. Clean. Prod.* **17**, 1–12.

Goel, R. B. A., Khalil, Z., Yendt, M. & Monteith, H. 2012 Implementation of carbon footprint model in a dynamic process simulator. Paper presented at the Water Environment Federation's Annual Technical Exhibition and Conference, New Orleans, LA.

Huxley, D. E., Bellamy, W. D., Sathyanarayan, P. & Ridens, M. 2009 *Greenhouse Gas Emission Inventory and Management Strategy Guidelines for Water Utilities*. Report of the Water Research Foundation. Water Research Foundation, Denver, CO.

IPCC 2006 2006 IPCC guidelines for national greenhouse gas inventories. In: *Prepared by the National Greenhouse Gas Inventories Programme* (H. S. Eggleston, L. Buendia, K. Miwa, T. Ngara & K. Tanabe, eds). IGES, Japan.

ISO 2006 *ISO 14040: 2006 Environmental Management: Life cycle assessment principles and framework (2nd edn)*. Report for the International Organization for Standardization. ISO, Geneva, Switzerland.

Jijakli, K., Arafat, H., Kennedy, S., Mande, P. & Theeyattuparampil, V. V. 2011 How green solar desalination really is? Environmental assessment using life-cycle analysis (LCA) approach. *Desalination* **287**, 123–131.

Johnston, A. 2011 Developing a Greenhouse Gas Emission Calculation Tool for Water Utilities. *MS Thesis*, Clemson University, Clemson, SC.

Lee, E. J., Criddle, C. S., Bobel, P. & Freyberg, D. L. 2013 Assessing the scale of resource recovery for centralized and satelite wastewater treatment. *Environ. Sci. Tech.* **47**, 10762–10770.

Leverenz, H. L., Tchobanogolous, G. & Asano, T. 2011 Direct potable reuse: a future imperative. *J. Water Reuse Desal.* **1**, 2–10.

Littrell, L. R., Robert, C. M., Macek, B. & Vignier, P. 2012 Piloting membrane replacements to improve RO optimization, reduce chemical use and reduce energy consumption. *Paper presented at the 2012 American Water Works Association Membrane Technology Conference*, Glendale, AZ.

Lundie, S., Peters, G. M. & Beavis, P. C. 2004 Life cycle assessment for sustainable metropolitan water systems planning. *Environ. Sci. Tech.* **38**, 3465–3473.

Lyons, E., Zhang, P., Benn, T., Sharif, F., Li, K., Crittenden, J., Costanza, M. & Chen, Y. S. 2009 Life cycle assessment of three water supply systems: importation, reclamation and desalination. *Water Sci. Technol.* **9**, 439.

Major, D. C., Omojola, A., Dettinger, M., Hanson, R. T. & Sanchez-Rodriguez, R. 2011 Climate change, water, and wastewater in cities. In: *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network* (C. Rosenzweig, W. D. Solecki, S. A. Hammer & S. Mehrotra, eds). Cambridge University Press, Cambridge, Cambridge, UK, pp. 113–143.

Meneses, M., Pasqualino, J. C. & Castells, F. 2010 Environmental assessment of urban wastewater reuse: treatment alternatives and applications. *Chemosphere* **81**, 266–272.

Mihelcic, J. R., Zhang, Q., Hokanson, D. R., Cornejo, P. K., Santana, M. V., Rocha, A. M. & Ness, S. J. 2013 *Feasibility Study on Model Development to Estimate and Minimize Greenhouse Gas Concentrations and Carbon Footprint of Water Reuse and Desalination Facilities*. Report for the WateReuse Research Foundation. WateReuse Research Foundation, Alexandria, VA.

Mo, W. & Zhang, Q. 2012 Can municipal wastewater treatment systems be carbon neutral? *J. Environ. Manage.* **112**, 360–367.

Mo, W. & Zhang, Q. 2013 Energy-nutrients-water nexus: integrated resource recovery in municipal wastewater treatment plants. *J. Environ. Manage.* **127**, 255–267.

Muñoz, I. & Fernández-Alba, A. R. 2008 Reducing the environmental impacts of reverse osmosis desalination by using brackish groundwater resources. *Water Res.* **42**, 801–811.

Muñoz, I., Rodriguez, A., Rosal, R. & Fernandez-Alba, A. R. 2009 Life cycle assessment of urban wastewater reuse with ozonation as tertiary treatment – a focus on toxicity-related impacts. *Sci. Total Environ.* **407**, 1245–1256.

Muñoz, I., Milà-i-Canals, L. & Fernández-Alba, A. R. 2010 Life cycle assessment of water supply plans in Mediterranean Spain. *J. Ind. Ecol.* **14**, 902–918.

MWH 2012 MWH Launches MCO2™ Greenhouse Gas Calculation Tool. Retrieved April 3, 2012. Available from: http://www.mwhglobal.com/blog/mwh-launches-mco2-greenhouse-gas-calculation-tool/.

Newman, P., Beatley, T. & Boyer, H. 2009 *Resilient Cities: Responding to Peak Oil and Climate Change*. Island Press, Washington, D.C.

Ortiz, M., Raluy, R. G. & Serra, L. 2007 Life cycle assessment of water treatment technologies: wastewater and water-reuse in a small town. *Desalination* **204**, 121–131.

Padowski, J. C. & Jawitz, J. W. 2012 Water availability and vulnerability of 225 large cities in the United States. *Water Resour. Res.* **48**, 1–16.

Pasqualino, J. C., Meneses, M. & Castells, F. 2010 Life cycle assessment of urban wastewater reclamation and reuse alternatives. *J. Ind. Ecol.* **15**, 49–63.

Peters, G. & Rouse, K. 2005 Environmental sustainability in water supply planning – an LCA approach for the Eyre Peninsula, South Australia. *Paper presented at the 4th Annual Australian Life Cycle Assessment Conference*, Sydney, Australia.

Raluy, R. G., Serra, L., Uche, J. & Valero, A. 2004 Life-cycle assessment of desalination technologies integrated with energy production systems. *Desalination* **167**, 445–458.

Raluy, R. G., Serra, L. & Uche, J. 2005a Life cycle assessment of desalination technologies integrated with renewable energies. *Desalination* **183**, 81–93.

Raluy, R. G., Serra, L., Uche, J. & Valero, A. 2005b Life cycle assessment of water production technologies – part 2: reverse osmosis desalination versus the Ebro River water transfer. *Int. J. LCA* **10**, 346–354.

Raluy, R. G., Serra, L. & Uche, J. 2006 Life cycle assessment of MSF, MED and RO desalination technologies. *Energy* **31**, 2025–2036.

Reffold, E. L. F., Choudhury, F. & Rayner, P. S. 2008 *Using Science to Create a Better Place: Greenhouse Gas Emissions of Water Supply and Demand Management Options*. Report of the UK Environment Agency. UK Environment Agency, Bristol, UK.

Santana, M. V. E., Zhang, Q. & Mihelcic, J. R. 2014 Influence of water quality on the embodied energy of drinking water treatment. *Environ. Sci. Technol.* **48**, 3084–3091.

Shrestha, E., Ahmad, S., Johnson, W., Shrestha, P. & Batista, J. R. 2011 Carbon footprint of water conveyance versus desalination as alternatives to expand water supply. *Desalination* **280**, 33–43.

Sobhani, R. & Rosso, D. 2011 Carbon and energy footprint analysis of an advanced oxidation process for removing NDMA in indirect potable water reuse operations. *Paper presented at the Water Environment Federation's Annual Technical Exhibition and Conference*, Los Angeles, CA.

Stillwell, A. S. & Webber, M. E. 2010 Water conservation and reuse: a case study of the energy-water nexus in Texas. Paper presented at the World Environmental and Water Resources Congress 2010: Challenges of Change.

Stokes, J. R. & Horvath, A. 2006 LCA methodology and case study life cycle energy assessment of alternative water supply systems. *Int. J. LCA* **11**, 335–343.

Stokes, J. R. & Horvath, A. 2009 Energy and air emission effects of water supply. *Environ. Sci. Technol.* **43**, 2680–2687.

Stokes, J. R. & Horvath, A. 2010 Supply-chain environmental effects of wastewater utilities. *Environ. Res. Lett.* **5**, 1–7.

Stokes, J. R. & Horvath, A. 2011a *Wastewater-Energy Sustainability Tool User's Manual*. Department of Civil & Engineering, University of California Berkeley, Berkeley, CA.

Stokes, J. R. & Horvath, A. 2011b *Water-Energy Sustainability Tool User's Manual*. Department of Civil & Environmental Engineering, University of California at Berkeley, Berkeley, CA.

Tampa Bay Water 2012 Energy water nexus – from greenhouse gases to utility energy optimization programs. Presentation for 2012 Energy Efficiency Global Forum, Water Research Foundation, Orlando, FL. Retrieved October 3, 2013. Available from: http://www.collab.waterrf.org/Workshops/FLwater/Florida%20WaterEnergy%20Coalition%20Documents/Florida%20Water%20Energy%20Workshop%20Presentations/Dave%20Bracciano%20Meribel%20Medina.pdf.

Tangsubkul, N., Beavis, P., Moore, S. J., Lundie, S. & Waite, T. D. 2005 Life cycle assessment of water recycling technology. *Water Res. Manage.* **19**, 521–537.

Tong, L., Liu, X., Yuan, Z. & Zhang, Q. 2013 Life cycle assessment of water reuse systems in an industrial park. *J. Environ. Manage.* **129**, 471–478.

UKWIR 2008 Carbon Accounting. Retrieved April 3, 2012. Available from: http://www.ukwir.org/site/web/news/carbon-accounting.

Zhang, Q. H., Wang, X. C., Xiong, J. Q., Chen, R. & Cao, B. 2010 Application of life cycle assessment for an evaluation of wastewater treatment and reuse project – case study of Xi'an, China. *Biores. Technol.* **101**, 1421–1425.

Zimmerman, J. B., Mihelcic, J. R. & Smith, J. 2008 Global stressors on water quality and quantity. *Environ. Sci. Technol.* **42**, 4247–4254.

First received 3 December 2013; accepted in revised form 25 March 2014. Available online 29 April 2014