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Review

Critical insights for a sustainability framework to address integrated community water services: Technical metrics and approaches

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ABSTRACT

Planning for sustainable community water systems requires a comprehensive understanding and assessment of the integrated source-drinking-wastewater systems over their life-cycles. Although traditional life cycle assessment and similar tools (e.g. footprints and emergy) have been applied to elements of these water services (i.e. water resources, drinking water, stormwater or wastewater treatment alone), we argue for the importance of developing and combining the system-based tools and metrics in order to holistically evaluate the complete water service system based on the concept of integrated resource management. We analyzed the strengths and weaknesses of key system-based tools and metrics, and discuss future directions to identify more sustainable municipal water services. Such efforts may include the need for novel metrics that address system adaptability to future changes and infrastructure robustness. Caution is also necessary when coupling fundamentally different tools so to avoid misunderstanding and consequently misleading decision-making.

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Contents

1. Introduction

In developed regions of the world, community water services are mostly achieved through large engineered centralized systems and through "siloed" water management approaches. Water services defined herein include the provision of safe drinking water, removal and treatment of sewage, and stormwater control. These services have been successful in controlling waterborne disease (OECD, 2011), mitigating flood damage (Jongman et al., 2012) and supporting firefighting (OECD, 2010) at an inexpensive market price (i.e. not full-cost). Increasing water demand, shrinking water resources, more stringent water quality goals, and aging infrastructure have resulted in a major asset management financial gap in countries like the US (US-EPA, 2002), threatening future affordability. Future planning will be more complex with rapidly developing economies and urbanization (WHO, 2012), the necessity to provide adequate ecosystem services (Wenning and Apitz, 2012) and to adapt to more intensified climatic change (IPCC, 2012). Overall, because of increases in population and decreasing water availability, coupled with continuously increasing service costs, and deficiencies in water system resilience, our current water services are not sustainable for future generations (Chang et al., 2012; Strengers and Maller, 2012).

A system level view of integrated water services is necessary to develop more balanced and optimal solutions. Focusing on just one part of the system, such as drinking water or wastewater alone, even when using system analysis tools such as life-cycle assessment (Ghimire et al., 2012; Igos et al., 2014; Lederer and Rechberger, 2010; Lundin et al., 2000; Memon et al., 2007; Mo et al., 2010, 2011; Remy and Jekel, 2008; Tangsubkul et al., 2005a; Tidåker, 2003; Venkatesh and Brattebø, 2012; WHO, 2012) may result in shifting problems to other sectors and miss more effective solutions only possible when the full system is viewed. For example, a full system approach that considers water-fit-for-purpose could lead to the removal of firefighting flow from drinking water provision. Additionally, framing water services around resource recovery (e.g., energy recovered from food and fecal residuals; nutrients returned to food production; and water largely retained within the municipal region) would yield very different system configurations and likely more robust and sustainable water services (Ashbolt, 2011; Otterpohl et al., 2003).

A major shift in resource governance would also be necessary to achieve such coordinated actions (Pahl-Wostl et al., 2012). Complications are evident when jurisdictional issues are raised by the various, and often conflicting stakeholders of source water (Winz et al., 2009) and municipal water services (Malmqvist and Palmquist, 2005). It is therefore no surprise that stakeholder-driven, and systems based approaches (Beall et al., 2011; Chang et al., 2012; Dobbie and Brown, 2014; Lundie et al., 2008; Maheepala et al., 2010; Malmqvist and Palmquist, 2005; Schlüter and Pahl-Wostl, 2007; Winz et al., 2009; Zarghami and Akbariyeh, 2012) are increasingly seen as appropriate ways to address and solve the complexities inherent to community water systems, and their fundamental interactions with regulators and users. Integrated community water management addresses total water cycle management via the engagement of key stakeholders that include city planners, citizens, regulators, utilities and managers of source water for a developed region (Thomas and Durham, 2003).

This paper addressed the overarching question: What are the strengths and weaknesses of various sustainability assessment tools used as a part of integrated community water management, and how do they aid in the design of next-generation community water services? We review a set

Table 1 – Example dimensions, objectives, tools and metrics for integrated municipal water management.

Dimension[a]	Objective	Tool[b]	Metric	Preferred direction	Key references/examples
Human Health	Characterize health effects from exposure to chemical and pathogen hazards	Risk assessment tools	Health-adjusted life years (HALYs), quality adjusted life years (QALYs), disability adjusted life years (DALYs), probability of infection, risk quotient	Minimized	Sometimes combined within the social dimension (Fane et al., 2002) Trade-off between disinfection by-products and pathogens (Havelaar et al., 2000b), Impacts of fecal-contaminated recreational waters (Schoen and Ashbolt, 2010)
	Assess exposure to chemicals and health effects	Life cycle impact assessment	Comparative toxicity units	Minimized	TRACI tool (Bare et al., 2008)
Economic	Capital and operational cost	Life cycle cost analysis	Life cycle cost ($)	Minimized	As used for distribution systems, rainwater use (Ghimire et al., 2012) decentralized wastewater (Wang, 2014) As proposed for green roofs (Carter and Keeler, 2008)
	Evaluate externalities	benefit-cost analysis	net present value ($)	Minimized	
	Characterize capital and operational costs, externalities, employment generation	Trip bottom line reporting	GDP and genuine progress indicator (GPI)	Maximized	Regional scale (Kubiszewski et al., 2013)
Environmental	Assess depletion of water, land and other natural resources	Footprints	Water and ecological footprints	Minimized	Regional, basin, and infrastructure scale (Boulay et al., 2013; Hoekstra and Hung, 2002; Moore et al., 2013; Zeng et al., 2012)
	Calculate energy use	Life cycle assessment (LCA), emergy	Life cycle energy consumption (mj), emergy (sej)	Minimized	Infrastructure scale, water, wastewater, stormwater treatment option (Igos et al., 2014; Lundin et al., 2000; Lyons et al., 2009; Remy and Jekel, 2008; Stokes and Horvath, 2006; Tangsubkul et al., 2005a; Tillman et al., 1998)
	Assess global warming potential	LCA, footprint	Life cycle global warming potential (g CO_2-eq), carbon footprint (g CO_2-eq)	Minimized	
	Assess eutrophication potential	LCA	Life cycle eutrophication potential (g N-eq)	Minimized	
	Assess impact to ecosystem services	Emergy	Emergy (sej)	Minimized, more renewable emergy and most efficient system	Regional, basin, global scale, and treatment options (Campbell and Garmestani, 2012)
Resilience	Evaluate the capacity to deal with change	Literature review and expert opinion, combinations of human health and environmental tools, CREAT	No standard metric- both qualitative and quantitative	Maximized	Limited to date (Cordell and Neset, 2014; Dessai and Hulme, 2007; US-EPA, 2013a), Novel aspects described in current paper

[a] Social and cultural dimensions are beyond the scope of our analysis.
[b] The overlapping areas of the research tools are described in Section 6 and Table 2.

of widely accepted sustainability tools/metrics, their applications to community water services, and potential missing attributes. While this paper focuses on the sustainability assessment tools and not the entire decision-making process, our review emphasizes how these tools can support the creative and adaptive capacities of civil society in a process to identify and assess options that may truly put our community water services on a more sustainable footing.

2. Current status of integrated municipal water management

Integrated Municipal Water Management (IMWM) addresses total water cycle management via the engagement of key stakeholders (Thomas and Durham, 2003). IMWM is a staged and iterative approach used by utilities to plan and manage water supply, wastewater and stormwater systems so as to minimize their impact or restore the natural environment; to maximize their contribution to social and economic vitality; and to engender overall community improvement (Maheepala et al., 2010). In the broader context, this approach is known as integrated resource management (IRM). While IMWM largely focuses on water and its social-environmental context, IRM deliberately spans the various resources (electricity, heat, material, water, nutrients etc.) associated with human systems, and may identify important synergies of other players with the water sector (e.g., co-digestion of food wastes with residuals organics from wastewater (De Gisi et al., 2014; Zeeman et al., 2008)).

While several groups have somewhat independently developed IMWM frameworks (Fuentes et al., 1996; Howe et al., 2011; Kärrman et al., 2011; Lundie et al., 2008; Maheepala et al., 2010; Malmqvist and Palmquist, 2005), all focus on six key components (Kärrman et al., 2011) including participation (why, when, and how stakeholders will participate) (Gabe et al., 2009; Lundie et al., 2008, 2006), vision (goals for the desired future), problem formation (identifying critical problems to be addressed), designing (identifying possible solutions), comparing (assessing among combinations of solutions to meet the vision), and choosing (decision-making and commitment). Often, stakeholder groups are formed to discuss, identify and state the problems to be addressed. As a following stage, three key pillars have been suggested to aid in designing possible solutions. They are composed of the access to a diversity of water sources facilitated by a diversity of centralized and decentralized infrastructure, provision of ecosystem services for the built and natural environment, and socio-political capitals for sustainability and water sensitive behaviors (Wong and Brown, 2009). While various categories of criteria have been suggested to evaluate the solutions, most fall into the following five primary groups including human health, economic, environment, social-cultural dimensions, and an overarching assessment of resilience to future challenges. Example technical metrics and tools to assess/compare community water-related options against stakeholders' objectives are described in Table 1.

Stakeholder participation and socio-behavioral aspects are fundamental in achieving the sustainability of community water services, yet there are various institutional and governance issues that hinder this approach, particularly perceived risks (Dobbie and Brown, 2014) and ‘the silos’ of water and resource governance (Pahl-Wostl et al., 2012). Numerous examples exist where the public have rejected water treatment approaches due to a lack of engagement or consideration of the socio-cultural aspects of the community (Hurlimann and Dolnicar, 2010; Stenekes et al., 2010). While we recognize the importance of social, cultural and governance aspects when selecting water service systems (Bertera, 2013), this paper primarily focuses on approaches for providing appropriate environmental, engineering, and human health perspectives in the context of informing deliberative stakeholder dialog. A broad range of tools and metrics exist to assess the sustainability of water systems from the technology to the service at watershed, country, and globe levels (Hester and Little, 2013). Here we narrow the list of technical metrics/approaches to those we consider critical to the built water services.

3. Water systems and key considerations

There are various ways to describe the built environment of community water services and associated watersheds. The water service interacts with a range of built and natural infrastructural systems in a complex network. The major flows and stocks of water, materials, energy and residuals are illustrated with conventional (solid boxes) and examples of possible future system elements (dashed boxes) in Fig. 1. This system view illustrates the interconnections within community water systems that tools and metrics need to address.

Starting with the environmental aspects illustrated in Fig. 1, there is a need to account for the many ecological processes and services that support human activities (Brauman et al., 2007; Cochran and Logue, 2011; Dodds et al., 2013). The natural components of the water systems include precipitation, land use, runoff, infiltration, evapotranspiration, surface water, and groundwater sources. These natural components provide source water to the built infrastructure system, process residuals/pollutants, support primary production, shape landscapes, and control local/regional climate. In return, the built infrastructure (i.e., infrastructure that collects, treats, and distributes water/wastewater/stormwater) influences the ‘natural’ environment through various flows, including leaks from distribution and collection systems, withdrawal from surface and groundwater sources, and discharges to surface and groundwater sources.

The conventional and example future systems (as shown with solid vs. dashed boxes in Fig. 1) differ with regard to the flows and stocks of water, energy, and nutrients. The conventional water infrastructure aims to withdrawal as much water resource to meet the demand and discharge stormwater as much and as fast as possible, resulting in an imbalanced hydrologic cycle and loss of ecosystem services. Alternative infrastructural choices restore the natural hydrology as well as attain other societal goals such as recovery of imbedded energy (via electricity production & heat capture), return of residual nutrients to food production, and maintenance of higher quality water for recreational use. Green and natural infrastructure such as rain gardens, permeable pavements, mature trees and green roofs incorporate natural capitals like vegetation and soil to manage stormwater and restore the

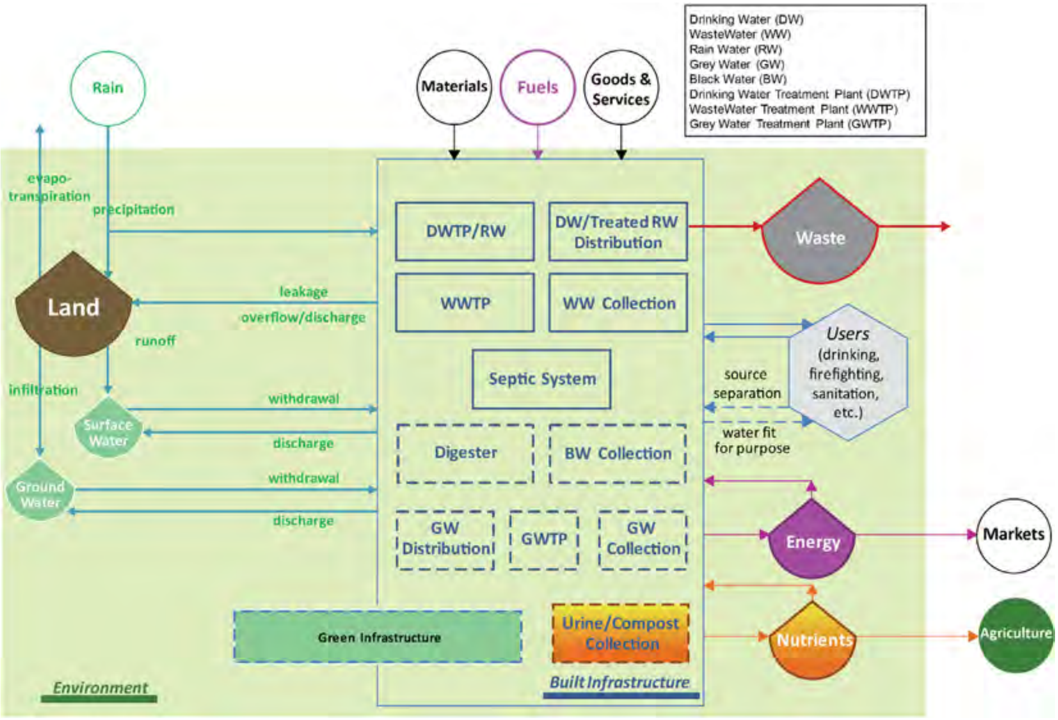

Fig. 1 – **System diagram illustrating key elements in community water services. The major flows and stocks of water, materials, energy and residuals of water systems are illustrated. The conventional configurations and example possible future system elements are described with solid and dashed boxes, respectively. DW, RW, GW, BW, DWTP, GWTP, WWTP represent drinking water, rain water, greywater, blackwater, drinking water treatment plant, greywater treatment plant, and wastewater treatment plant, respectively. The arrows represent emergy flows. While the circles mean outside sources of energy, the semicircles describes various storage compartments.**

natural hydrological cycle (US-EPA, 2008; Romitelli, 1997; Arden, 2014). Constructed wetlands can be used to simulate natural wetlands and use renewable energy derived from natural systems to replace fossil fuel energy used in conventional treatment technologies to achieve the required purification of water, and restore the hydrological cycle through increasing evapotranspiration and filtration (Odum, 1983).

Current community water services negatively influence nitrogen and phosphorus cycles by releasing large amount of nutrients as waste via combined sewage overflow, wastewater effluent discharge, and sludge application (Tangsubkul et al., 2005b; Tillman et al., 1998), and emitting greenhouse gases during water and wastewater conveyance and treatment (Short et al., 2014). Nitrogen and phosphorus contamination via wastewater is one of the major reasons for nutrient cycle disruption, leading to eutrophication and hypoxia in many coastal and riverine regions (US-EPA, 2013b). Alternative system elements such as urine-diversion toilets and blackwater-only sewers can contain these nutrients for food production and avoid their direct release to the environment, promoting restoration of nutrient cycles.

The example novel system elements capitalize on recent research that identifies decentralized/semi-decentralized systems as more sustainable for the environment (Luthy, 2013). As shown in Fig. 1, the specific decentralized/semi-decentralized processes may include greywater treatment and local reuse (either at the household or community scale); blackwater co-digestion with food waste for energy recovery; diverted urine and feces for fertilizer and soil conditioner (Zeeman et al., 2008); and rainwater harvesting. Greywater accounts for some 70% of residential wastewater in a conventional sewer; separating, treating, and reusing greywater onsite would reduce demand on the outside water resource by up to 70% compared to conventional centralized water systems (and the energy used in its conveyance). Treated greywater has been reliably used for purposes such as irrigation, toilet flushing, and clothes washing in Australia (Barker et al., 2013). Local rainwater harvesting could also provide additional municipal water sources, depending on the level of treatment. Local rainwater harvesting has the extra benefit of enhancing system resilience to storm events, drought and water shortage (Jones and Hunt, 2010).

Essentially, the proposed novel elements change the perspective on water services from the “siloed” and centralized water management thinking into integrated and decentralized/semi-decentralized design following the principles of biomimicry and resource recovery. While the novel elements may present significant potentials in mitigating energy use, resource consumption and nutrient export, the system performances with individual novel elements from environmental, economic, and social perspectives are still not fully understood. The following discussion presents technical tools and metrics that allow us to compare the performances of conventional and alternative community water systems as presented in Fig. 1 across the dimensions presented in Table 1.

4. Metrics and tools for addressing infrastructural system aspects

We acknowledge that human health, economy, and ecosystem impacts are intertwined. However, we have chosen to classify them separately in order to discuss the metrics and tools explicitly.

4.1. *Human health risk assessment*

The purpose of the human health assessment is to compare the adverse health effects potentially caused by exposures to hazards from water systems. The National Research Council (NRC) risk assessment framework (NRC, 2009) outlines the general steps required to assess risk from microbial and chemical hazards. For the water systems considered, various pathogens (viral, bacterial, parasitic protozoan and helminths) and chemicals (disinfection byproducts, pesticides, metals, etc.) are relevant. When ingested, inhaled, or absorbed through the skin, these pathogens and chemicals may result in a range of health outcomes from acute illness to chronic disease and mortality. Therefore, an ideal human health metric incorporates these various health outcomes. The Health-Adjusted Life Year (HALY) is a class of metrics that transforms any type of morbidity or mortality into an equivalent number of life years (Hofstetter and Hammitt, 2002). The two most common HALYs are Quality Adjusted Life Years (QALY) which measure the actual health quality integrated over time, and the QALY compliment, the Disability Adjusted Life Years (DALYs). DALYs are the sum of years of life lost by premature mortality and years lived with disability (Murray and Acharya, 1997). To calculate DALYs, the time lived with a disability is multiplied by a disability weight to make it comparable with the years of life lost due to premature mortality. In this way, both non-fatal and fatal health outcomes can be considered and compared.

Of the two most commonly reported HALYs, DALYs have been used as a human health metric to compare water system alternatives when health outcomes are seemingly disparate (An et al., 2011; Boulay et al., 2011; Haller et al., 2007; Havelaar and Melse, 2003; Havelaar et al., 2000b; Lundie et al., 2008). Havelaar et al. (2000a) discussed the risks and benefits of drinking water disinfection using the DALY; specifically, the tradeoff between the benefit of reduced microbial infection when implementing ozonation and the potential dis-benefit of an increase in renal cell cancer from the formation of disinfection byproducts was quantified. Since these health outcomes are different in duration, magnitude and impact, overall risk was characterized using the DALY. The analysis supported the use of drinking water disinfection with: "the health benefits of preventing gastroenteritis in the general population and premature death in patients with acquired immunodeficiency syndrome outweighing health losses by premature death from renal cell cancer". However, the magnitude of the overall disinfection benefit varied considerably when key, uncertain parameters were changed, such as the severity weight for gastroenteritis. Furthermore, the DALY was limited by a lack of knowledge and available data for the population exposure assessment. Other potential health metrics, although also dependent upon the same exposure assessment methods, are less data intensive and do not require illness severity and duration data. For example, the probability of infection (Agulló-Barceló et al., 2012; Åström et al., 2007) and the risk quotient (Al Aukidy et al., 2012; Leung et al., 2013), i.e., the observed hazard concentration divided by the acceptable level (NRC, 2012), are useful for a quick comparison of potential risk within a class of hazards.

Risk quotients have been used to evaluate the potential health risks associated with pathogen (adenovirus, *Norovirus*, *Salmonella*, and *Cryptosporidium*) and chemical (DBPs, hormones, pharmaceuticals, pesticides, and other chemicals) for hypothetical wastewater reuse scenarios (NRC, 2012). The probability of infection associated with water and wastewater system use has been assessed separately for conventionally treated drinking water (Petterson, 2010; Teunis et al., 2010; Westrell et al., 2003, 2004), contact with wastewater (Charles, 2009; Schoen and Ashbolt, 2010; Soller et al., 2010), rainwater reuse (Ahmed et al., 2014, 2011), and greywater reuses (Barker et al., 2013).

There is limited analysis that considers the entire community water and wastewater system (Katukiza et al., 2014) and alternative, decentralized system options (Ashbolt et al., 2006). When comparing water system alternatives, the adverse health effects will differ in magnitude for each system option depending on the hazards unique to each water resource, the routes of exposure, and the failure/event impacts of each technology. Computing all the human health metrics for each option is time consuming and unnecessary. Moving forward, the probability of illness and risk quotient can be assessed in a screening-level assessment to identify the most critical human health hazards, for which the DALY is estimated. These metrics may be computed over different time scales to correspond to the functional units and expected system life-times defined by the life cycle assessment and the overall system-level risks as long as the variation in health burden is captured.

4.2. *Economic aspect: cost analysis*

A key, often overriding consideration in any decision related to investment in water infrastructure is the cost. Various methods such as life cycle cost and benefit-cost analyses exist to quantify the costs of water services. While large upfront costs often dominate the discussion of options for providing water services in current centralized systems, the goal of a more complete cost analysis is to weigh initial, direct costs together with costs occurring over the entire life cycle of a system and together with indirect, environmental, societal costs. Examples of direct upfront costs include the costs of planning, materials, and labor. Often, life cycle costs include direct costs associated with materials, constructing, operating, maintaining, and eventually decommissioning or repurposing infrastructure for parts of entire water systems.

Beyond life cycle costs, there are a number of indirect, environmental or societal costs and benefits which should be considered. These include, the cost of health effects caused by air emissions associated with the electricity used to pump and treat water and wastewater (Fann et al., 2013; Pabi et al., 2013), the cost to heat household hot water (Morales et al., 2013), the cost associated with increased illness from recreational and drinking water pathogen exposures (Collier et al., 2012; Dwight et al., 2005), the cost of imbalanced hydrological cycle and the diversion of water flows from ecological needs versus the electricity savings associated with the increased insulation provided by a green roof (Clark et al., 2008), or the value of green space and natural infrastructure in an urban area provided by rain gardens, vegetation, wetlands or aquifers used for wastewater and stormwater management (Bowman et al., 2012; Page, 2010).

Benefit-cost analysis (BCA), often incorporating a variety of direct and indirect costs and benefits, aims to provide a quantitative assessment in monetary terms for decision making (Arrow et al., 2004; Mishan, 1978). Although BCA has been applied to assess the costs and benefits of various infrastructure projects and policies, the BCA approach has been challenged in the following aspects. First, due to the difficulty to forecast causal relationships, errors such as omitting certain costs and benefits may occur. Second, the ambiguity and uncertainty involved in quantifying and assigning a monetary value to intangible items could lead to an inaccurate analysis. Third, the choice of discount rates can significantly influence the estimated net present values of BCA. Last, BCA assumed the distribution of costs and benefits could theoretically be *corrected* via transfer payments, which may result in double counting.

Moving forward, the coupling of economic impact analyses with sensitivity analysis can identify the influences of key parameters (such as discount rates), incorporate the distributional effects of a decision (US-EPA, 2010), and consdiser a full specturm of costs and benefits connected with risk and life cycle assessment (Hardisty et al., 2013). In addition, there is a need to build a body of knowledge regarding the cost and benefit outcomes associated with less common options for providing water services such as those based on principles of water fit-for-purpose, source-separation of waste streams, material/energy recovery, and the use of natural processes for water treatment. A research agenda to address these issues should include the development of standardized datasets, which can be combined in various configurations to support efficient and fair comparisons of a wide variety of system options. These datasets should support the incorporation and attribution of multiple benefits such as those indirect costs discussed above as well as electricity recovery from biogas, the reuse of nutrient-dense streams and the avoidance of fertilizer production and waste management, capture and reuse of rainwater, and the reuse of greywater for non-potable purposes. It should also include efforts to bound the uncertainty and specify a wide range of human health (Fann et al., 2013) and environmental impacts (Daily and Matson, 2008).

4.3. *Ecosystem outcomes*

Life cycle assessment, footprint analyses and thermodynamic approaches such as emergy analysis are widely utilized tools to assess environmental impacts of products and processes at system levels. The strengths and weaknesses of applying these tools in water resource and infrastructure management are described below.

4.3.1. *Life cycle assessment of water systems*

Life Cycle Assessment (LCA) is a well-established method for quantifying energy consumption and environmental impacts through the entire life-cycle of a product or process. In water systems, a life cycle inventory tracks the energy and material inputs for producing, constructing, operating, and maintaining water and waste services, and associated releases into the air, water and soil environments. Life cycle impact assessment quantifies specific aspects of environmental and human health impacts of services in terms of global warming, eutrophication, acidification, ozone depletion, photochemical oxidation, ecotoxicity, and non-carcinogenic and carcinogenic human health impacts.

LCA approaches have been widely used to analyze the direct and indirect environmental impacts of specific water management elements, i.e., various options for drinking water supply systems, wastewater conveyance and treatment, stormwater management, biosolid systems, or treatment chemicals such as disinfectants and coagulants. A number of comparative LCA studies have provided the comparative energy and environmental evaluation of water system elements at household, community, and city scales in order to assist in selecting preferred options (Lyons et al., 2009; Stokes and Horvath, 2006, 2009; Stokes et al., 2013). The life cycle environmental impacts of water service options are influenced by the choice of system boundaries, functional units, allocation methods, embedded databases, and life cycle impact assessment approaches. The majority of these studies illustrate that the operation phase is the dominating contributor to impacts, compared with the design, construction and demolition phases. The relative contributions of electricity and chemicals are variable, depending on the energy mix, specific treatment technology and local topographic condition. Depending on the choice of life cycle impact assessment approaches, diverse performance indicators are available to evaluate the environmental and human health impacts of water services. However, energy and nutrient related impacts appear to dominate for water services, suggesting a limited number of key LCA measures for water systems, such as global warming potential, energy use and eutrophication potential, as a good starting point for LCA of water systems.

However, there are still shortcomings related to the application of LCA approaches for assessment of water services, such as the lack of consideration of water scarcity, disruption of natural hydrology and impacts of climate and demographic change. Further, several aspects of LCA methodology are still under development, including incorporation of uncertainty and variability assessment, integration of system dynamic processes, inclusion of ecosystem services, reflection of appropriate temporal and spatial scales, and improvement of impact assessment tools.

LCA studies that evaluate the whole anthropogenic water cycle from water extraction to wastewater recycle and reuse are generally lacking (Lundie et al., 2004). Furthermore, LCAs in water systems have yet to explore issues perceived as major concerns of fit-for-purpose water reuse schemes (e.g., pharmaceuticals, personal care products, disinfectant byproducts, pathogens and brine concentrates) (Richardson et al., 2011). There is also little scientific consensus for how to comprehensively assess environmental and human health impacts of water use, although a number of methods and indices have been developed to compile water use inventories, and generate midpoint and endpoint methods for addressing water scarcity (Boulay et al., 2011, 2013; Hanafiah et al., 2011; Pfister et al., 2009).

In order to improve current limitations, the future water LCA efforts should include 1) compiling the life cycle inventory of the whole anthropogenic water cycle including both centralized and decentralized options, 2) development of impact assessment tools to evaluate the environmental and human health impacts of water scarcity and emerging contaminants, and 3) integration with additional pieces such as chemical and microbial associated risk assessment, footprints, emergy, and resilience analysis.

4.3.2. *Footprint approaches*

The “footprint family” of environmental indicators, including carbon footprint (Wiedmann and Minx, 2008), ecological footprint (Wackernagel and Rees, 1996) and water footprint (Zeng et al., 2012), applies life cycle thinking to analyze the environmental releases and resource requirements of products and processes. The Carbon Footprint (CF) for water services accounts for the global warming gas emissions during the design, construction, operation, and decommission stages of community water infrastructure. The Ecological Footprint (EF) (Wackernagel and Rees, 1996) measures the productive land area required to supply the resources consumed and to assimilate the residuals (e.g., CO_2, nitrogen in wastewater) generated for a process or a product or a region. The Water Footprint (WF), initially introduced by Hoekstra and Hung (Hoekstra and Hung, 2002) is analogous to the “ecological footprint” and is used to estimate the volume of water required for the production of goods and services.

Although footprint analysis may provide insight into the design and management of water services, further development and novel indicators are probably necessary in order to form a comprehensive understanding of community water systems and to aid in strategic planning for more sustainable water systems. To date, CF's have been described for production and distribution of drinking water (Mo et al., 2011), collection and treatment of wastewater (Remy and Jekel, 2008), and the handling of sludge (William and Mciwem, 2009). Despite valuable attempts to assess community water systems, the CF arising from the holistic analysis of the drinking, stormwater and wastewater systems requires further development in order to provide an integrated assessment of the built environment water cycle, and more importantly, to provide a systems-level view also suited to assess radically different options. Typical EFs of water services are limited to the measurement of land area, and carbon dioxide emissions during transport and processing of municipal water. The EF does not account for hazardous (chemical and microbial) environmental releases, nor does it measure water (surface and ground) resource availability. The WF is limited to the analysis of embodied virtual water, such as in a nation's economy and to trace water-intensive stages along products' supply chains (Hoekstra et al., 2011). Shortcomings of the WF concept which hinder its use for designing next generation water systems include: 1) an incomplete accounting of the natural and built environment water cycle (Chapagain and Tickner, 2012), 2) limited capability to characterize the temporal and spatial variability of watershed hydrology and related water resource availability (Zeng et al., 2012), 3) no description of ecosystem services, 4) lack of an appropriate description of the environmental and human health risks associated with municipal water (Pfister and Ridoutt, 2013), and 5) an inability to provide solutions towards water resource management and infrastructure design (Chapagain and Tickner, 2012).

In order to overcome the above shortcomings of water footprint for water infrastructure design, the following additional approaches are suggested: 1) incorporation with an integrated bio-physical model to describe natural and the built water cycle with appropriate temporal and spatial resolution; and 2) combination with life cycle impact, risk, emergy analyses to provide a comprehensive understanding of hydrology, environmental and human health risks, and role of ecosystem services.

4.3.3. *A thermodynamic approach: emergy analysis*

Emergy analysis is a system-based method applicable to various scales that incorporates environmental, social, and economic aspects into a common unit of nonmonetary measure (solar energy equivalent joule, sej). Emergy is defined as the available energy of one kind previously used directly and indirectly to make a service or product (Odum, 1996). It is based on the observation of the patterns of energy flows in ecosystems and economic systems during self-organization. It is based on the theory that all systems (ecological, social and economic) are centered on the transformation of available energy. For example, the transformity values (total emergy input required to generate one unit of energy out) for wind energy, and phosphate fertilizer are 1.5E3 sej/J, and 1.0E7 sej/J) (Odum, 1996). This means that the processes generating phosphate fertilizer require considerably more upstream energy investment (geological sedimentary cycle for phosphorus rock to regenerate and the fossil fuels needed in mining and formulating it as fertilizer) than what it takes to regenerate wind energy.

Distinct from the aforementioned approaches, emergy accounting provides a unique platform to combine economic activities (mainly water needs and water disposal) and the hidden ecological costs (via ecosystem services) into a common measuring unit, sej. It represents a fundamental change in perspective from a user-based (i.e., monetary exchange) to donor-based (energy used) value system. This approach allows the behavior of a system as a whole and the interactions between subcomponents to be observed and optimized. This can be applied to water systems with varied components such as water in biological systems, various source waters, drinking water, wastewater, and stormwater. In addition, emergy theory implies that prevailing systems are those where designs maximize available energy by reinforcing resource intake optimally. This statement includes maximizing the resource intake and operating at the optimum efficiency for maximum productivity (Odum, 1996). The same holds for water systems, particularly for community water services. Hence, the current water management seeking endless sources of new supply, rather than maximizing the productivity and efficiency of the whole system, is not sustainable.

Moving forward, the whole water systems including both natural and built components should be assessed with emergy approach. Although emergy analysis is capable of addressing different scales of systems, it has not been reported for complete community water systems. Rather, emergy studies have largely focused on only one of the subsystems, such as drinking water treatment (Arbault, 2013; Buenfil, 2001), the water distribution system (Buenfil, 2001), wastewater treatment and health effects (Björklund, 2001), wetland treatment (Arias and Brown, 2009; Nelson, 1998), the natural hydrological cycle (Watanabe, 2014), or watersheds (Romitelli, 1997). In addition, the alternative water systems which incorporate hydrological restoration and resource (energy, carbon, nutrients, and water) recovery should be emphasized in the future research agenda for community water services.

5. System resilience and adaptability

While there are many interpretations of resilience, we have adopted a definition suitable for infrastructures, "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions" (Stockholm Center, 2007). The concept of resilience was developed for systems where humans and nature co-exist, and describes the capacity of the system to remain within desired states given changing conditions (Folke, 2010). For water services, the desired or operative state provides for critical services such as public health protection, drinking water supply and sanitation needs (Howard et al., 2010).

To enhance the resilience of a community water system to disruptions, improving adaptability of the natural-engineered system is as important as strengthening social preparedness through governance, community outreach and education (Ananda and Proctor, 2013; Bettini et al., 2013; O'Rourke, 2007). The US EPA provides a set of tools (such as CREAT, CBWR, VAST, and WHEAT) to assess the vulnerability of water, wastewater, and combined utilities to loss of service due to natural and human induced risks (US-EPA, 2013a). Most of these tools focus on emergency management planning and stakeholder engagement to identify and improve communication with relevant interconnected stakeholders (i.e., hospitals, agriculture, and power system operators). A few of them include a narrative analysis of adaptive measures to climate change (such as CREAT). While we recognize the importance of the social dimensions, this paper aims to review resilience assessment frameworks that relate to the built infrastructure and interconnected environmental elements with the purpose of ranking alternative engineered water services.

There is no standard resilience assessment approach or metric. Ideally, the assessment should be participatory and identify the system components and interactions, critical requirements for system operation, and potential future changes (Stockholm Resilience Center, 2007). Although both qualitative and quantitative approaches were proposed, qualitative approaches to assess resilience are more common in the literature. Balsells et al. qualitatively compared the resistance, absorption and recovery capacitates of alternative stormwater management options for flooding conditions in Rotterdam and New Orleans (Balsells et al., 2013). The WHO presented a qualitative resilience assessment to identify the vulnerability and adaptive capacity of water services to future climate changes, such as precipitation frequency and intensity (WHO, 2010). On the other hand, Ayyub et al. suggested quantitative resilience metrics incorporating a measure of robustness and rapidity of recovery for various qualities of interests under event disruptions (Ayyub, 2014). Similarly, Hwanga computed a simplified resilience metric as the volume of water not supplied to customers over the duration of a pipe failure event (Hwanga et al., 2013). We are not aware of any applications of a quantitative measure of resilience for a community water system that assesses the multiple dimensions in Table 1 or complex challenge events, such as climate change, hurricane, flooding or drought.

The major limitation of the existing work is the lack of a broad scope of impacts such as energy consumption, ecosystem services, and economic evaluation (Ayyub, 2014). A second limitation is the lack of a comprehensive resilience assessment of both long-term changes and event disruptions. Moving forward, assessing the resilience of alternative water systems should explicitly consider the robustness, adaptive capacity, and rapidity as they relate to the critical requirements identified for the community across the different challenges including population change, climate change, and catastrophic events, either qualitatively or quantitatively. A screening-level qualitative metric based on descriptive summaries of evidence from literature and expert opinions will likely pull from the data collected to estimate the other metrics, such as technical specifications, performance data, or water demand. Following the screening-level assessment, a quantitative metric may be calculated for key challenges —either disruption or system change- and qualities of interest. The quantitative metric will likely require the use of tools previously described to estimate the impact of a challenge on critical services over the duration of the challenge. For example, QMRA may be used to estimate the health impact (in DALYs) resulting from a flooding event over the course of the event and the recovery, given alternative adaptive measures. The resulting health impacts time series can then be used to calculate the robustness and rapidity in combination with other information on time to recovery for the human health dimension of resilience.

6. Overlapping and different foci of the tools

Despite different methodological roots, the discussed tools share overlapping research interests and concerns (Table 2). For example, while the foci of water footprint and water-focused life cycle impact assessment are different, both tools can provide quantitative metrics to support water resource management. The existing water footprint relies on water use indicators in the inventory phase, assuming existing per capita demand will continue. In contrast, the LCA practices emphasize impacts in the areas of human health protection, ecosystem quality, and resources, based on

Table 2 – Considerations included in the discussed tools.

Considerations		Life cycle assessment[a]	Water footprint[b]	Emergy analysis	Human health risk assessment	Life cycle cost	Benefit-cost analysis[c]	Resilience assessment[d]
Energy Use	Direct energy consumption	X		X		X	X	
	Indirect energy consumption from supply chains	X		X		X	X	
	Energy consumed in the built processes	X		X		X		
	Energy consumed in natural processes			X				
Risks	Direct human health risks	X			X		X	X
	human health risks from supply chain activities	X					X	
	Human health risks from discharge or disposal of products	X			X		X	
	Accidental human health risks				X		X	X
	Occupational human health risks							
	Ecological risks due to the depletion of natural resources	X		X				
Costs	Cost for built processes during design, construction, operation, & decommission stages			X		X	X	X
	Cost for Environmental services			X			X	
Water Use	Direct water consumption	X	X	X		X	X	X
	Indirect water consumption from supply chain/life cycle processes	X	X			X	X	
	Natural water flows	X	X	X				
	Anthropogenic water flows	X	X	X				X

[a] The current practices include neither microbial related risks, nor a complete description of natural and anthropogenic water flows.

[b] The current practices don't contain a complete description of natural and anthropogenic water flows.

[c] The current practices include the environmental and human health consequences which can be monetized.

[d] The most common reported considerations for water systems from literature review are checked in Table 2.

freshwater use inventories and cause-effect chains. Similarly, risk assessment, life cycle impact assessment, and benefit-cost analysis are capable of evaluating the risks of water systems. These three methods differ in the coverage of risks and spatial and temporal resolutions. Life cycle impact assessment systematically evaluates direct, upstream and downstream risk, and risk to built and natural environment. Benefit-cost assessment has a similar coverage but it is generally limited by inclusion of endpoints that can be monetized. Risk assessment may be directed to local microbial and chemical risks due to human exposure of the water flows. Additionally, both emergy analysis and LCA can assess the indirect energy consumption of water systems. The life cycle energy consumption includes the direct and indirect energy consumption from the built processes. In addition to the energy consumption captured by LCA and emergy analysis, the emergy method also accounts for the embedded energy (beyond fossil fuel-based energy) of the supporting natural resources (e.g., groundwater stocks, wetlands, rain and evaportranspiration flows).

Resilience assessment may include any of the considerations relevant to the protection of the human health, a reliable supply of water, ecosystem services, or others depending on the identified critical water services. The most reported considerations for water systems are water supply and human health, marked in Table 2. Ultimately, the considerations of the resilience assessment are specific to the selected future challenges and critical services of the water system. Resilience assessment overlaps in considerations with many of the previously listed tools, but with a view toward performance under future change or challenge rather than nominal conditions.

7. Coupling metrics/tools for integrated water management

Coupling multiple tools appropriately has the potential to better capture the complexities of water systems at different levels and provides a more comprehensive view of sustainable water management. For example, the combination of life cycle assessment, risk assessment and emergy analysis could evaluate the performances of a water system for environmental, built infrastructure and human health dimensions. The human health risk assessment tools provide detailed assessment of chemicals and microbes of water systems, which are currently lacking in other tools like life cycle impact assessments and emergy analysis. Emergy analysis provides a description of ecosystem service landscape where the built infrastructure resides, an important perspective lacking in both life cycle impact and human health risk assessment.

In addition, in order to promote the selection of systems which are robust against hazardous events and resilient in the face of long-term societal or climatic changes, it is important to consider the effect of relevant events and scenarios on the metrics provided by each tool. Too often decisions are focused on nominal and near-term conditions, not including lower probability but high risk failure events and future changes. Resilience assessment could identify the challenges and opportunities for water systems to recover from, and adapt to, long-term and short-term hazards.

The challenge when coupling multiple complex metrics is to convey the objective and scope of each tool and the magnitude as well as uncertainty of each metric, and use them to inform the decision process, together with other social, legal, fiscal considerations and obligations. In practice, time and resource constraints make it difficult to apply all tools and collect all of the information one would ideally synthesize for decision-making. Therefore, a tiered framework for calculating multiple metrics for water systems needs to be developed (Lundie et al., 2008). When presenting results for system options across multiple metrics, it is important to communicate the relative uncertainty for each metric to allow for proper interpretation of qualitative and quantitative results. All of the tools described here involve the use of variable and uncertain inputs for calculation. To represent these sources of uncertainty and variability, metrics are best presented as probabilistic distributions or with error bars. Important information is lost when only considering the best estimate or median results.

Overall, the sustainability tools described above represent distinct research foci, different spatial and temporal resolutions, and various fields of application. Although appropriately coupling these tools can potentially provide a more complete system perspective for various dimensions than a single tool, caution should be taken to clarify the system boundaries and to ensure proper development of the sustainability tools.

8. Conclusions

We conclude that a comprehensive assessment of the whole water cycle (both built and natural water components) and full community water services (including water resources, drinking water, sanitation, firefighting, irrigation, stormwater, wastewater management and ecosystem services) is required to evaluate system sustainability and simply not move issues to other domains and cause unintended consequences. Comprehensive assessment across the entire water cycle that addresses environmental, economic, and human health aspects are lacking. Examples of metrics and tools for such a comprehensive approach are available (Table 1), but their method and dataset limitations for quantifying ecosystem services related to community water systems, novel water system configuration, synergistic water-energy-carbon-fertilizer nexus, and system adaptability to future changes all require further research. Often, they are rarely combined into an integrated sustainability framework to evaluate the built water system without compromising natural water services. Therefore, an imminent research need is the demonstration of this integrated approach with real case studies to support decision making.

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REFERENCES

Agulló-Barceló, M., Casas-Mangas, R., Lucena, F., 2012. Direct and indirect QMRA of infectious Cryptosporidium oocysts in reclaimed water. J. Water Health 10 (4), 539–548.

Ahmed, W., Gardner, T., Toze, S., 2011. Microbiological quality of roof-harvested rainwater and health risks: a review. J. Environ. Qual. 40 (1), 13–21.

Ahmed, W., Brandes, H., Gyawali, P., Sidhu, J.P., Toze, S., 2014. Opportunistic pathogens in roof-captured rainwater samples, determined using quantitative PCR. Water Res. 53, 361–369.

Al Aukidy, M., Verlicchi, P., Jelic, A., Petrovic, M., Barcelo, D., 2012. Monitoring release of pharmaceutical compounds: occurrence and environmental risk assessment of two WWTP effluents and their receiving bodies in the Po Valley, Italy. Sci. Total Environ. 438, 15–25.

An, W., Zhang, D., Xiao, S., Yu, J., Yang, M., 2011. Quantitative health risk assessment of *Cryptosporidium* in rivers of southern China based on continuous monitoring. Environ. Sci. Technol. 45 (11), 4951–4958.

Ananda, J., Proctor, W., 2013. Collaborative approaches to water management and planning: an institutional perspective. Ecol. Econ. 86, 97–106.

Arbault, D., 2013. Emergy evaluation of water treatment processes. Ecol. Eng. 60 (0), 172–182.

Arden, S., Ma, X., Brown, M., 2014. Ecohydrologic Effects of Urbanization on Evapotranspiration in Shallow Groundwater Table Environments. Water Sci. Technol. 70 (11), 1789–1797 (Special Issue: Modeling the Urban Water Cycle).

Arias, M.E., Brown, M.T., 2009. Feasibility of using constructed treatment wetlands for municipal wastewater treatment in the Bogotá Savannah, Colombia. Ecol. Eng. 35 (7), 1070–1078.

Arrow, K.J., Cropper, M.L., Eads, G.C., Hahn, R.W., Lave, L.B., Noll, R.G., Portney, P.R., Russell, M., Schmalensee, R., Smith, V.K., Stavins, R.N., 2004. Is there a role for benefit-cost analysis in environmental, health, and safety regulation? Science 272, 221–222.

Ashbolt, N.J., 2011. The Short Pipe Path – Safe Water, Energy & Nutrient Recovery. Session 18: Zero Net Energy Facilities and the Future of Wastewater Treatment. Water Environment Foundation, Hyatt Regency McCormick Place, Chicago, Illinois, pp. 1233–1241.

Ashbolt, N.J., Petterson, S.R., Westrell, T., Ottoson, J., Schönning, C., Stenström, T.A., 2006. In: Malmqvist, P.-A., Heinicke, G., Kärrman, E., Stenström, T.A., Svensson, G. (Eds.), Strategic Planning of Sustainable Urban Water Management. IWA Publishing, London, pp. 43–62.

Åström, J., Petterson, S.R., Bergstedt, O., Pettersson, T.J.R., Stenström, T.A., 2007. Evaluation of the microbial risk reduction due to selective closure of the raw water intake before drinking water treatment. J. Water Health 5 (s1), 81–97.

Ayyub, B.M., 2014. Systems resilience for multihazard environments: definition, metrics, and valuation for decision making. Risk Anal. 34 (2), 340–355.

Bare, J.C., Norris, G.A., Pennington, D.W., M, T., 2008. TRACI the tool for the reduction and assessment of chemical and other environmental impacts. J. Ind. Ecol. 6 (3–4), 49–78.

Balsells, M., Barroca, B., Amdal, J.R., Diab, Y., Becue, V., Serre, D., 2013. Analysing urban resilience through alternative stormwater management options: application of the conceptual Spatial Decision Support System model at the neighbourhood scale. Water Sci. Technol. Water Supply 68 (11).

Barker, F.S., O'Toole, J., Sinclair, M.I., Leder, K., Malawaraarachchi, M., Hamilton, A.J., 2013. A probabilistic model of norovirus disease burden associated with greywater irrigation of home-produced lettuce in Melbourne, Australia. Water Res. 47 (3), 1421–1432.

Beall, A., Fiedler, F., Boll, J., Cosens, B., 2011. Sustainable water resource management and participatory system dynamics. Case study: developing the Palouse Basin participatory model. Sustainability 3 (4), 720–742.

Bertera, W.J., 2013. Envision: a sustainability guide for water professionals. J. Am. Water Works Assoc. 105 (7), 50–53.

Bettini, Y., Brown, R., de Haan, F.J., 2013. Water scarcity and institutional change: lessons in adaptive governance from the drought experience of Perth, Western Australia. Water Sci. Technol. 67 (10), 2160–2168.

Björklund, J., 2001. Emergy analysis of municipal wastewater treatment and generation of electricity by digestion of sewage sludge. Resour. Conserv. Recycl. 31, 293–316.

Boulay, A.M., Bulle, C., Bayart, J.B., Deschenes, L., Margni, M., 2011. Regional characterization of freshwater use in LCA: modeling direct impacts on human health. Environ. Sci. Technol. 45, 8948–8957.

Boulay, A.M., Hoekstra, A.Y., Vionnet, S., 2013. Complementarities of water-focused life cycle assessment and water footprint assessment. Environ. Sci. Technol. 47 (21), 11926–11927.

Bowman, T.T., C, J., Thompson, J., Kliebenstein, J., Colletti, J.P., 2012. Multiple approaches to valuation of conservation design and low-impact development features in residential subdivisions. J. Environ. Manag. 2012 (104), 101–103.

Brauman, K.A., Daily, G.C., Duarte, T.K., Mooney, H.A., 2007. The nature and value of ecosystem services: an overview highlighting hydrologic services. Annu. Rev. Environ. Resour. 31 (1), 67–98.

Buenfil, A., 2001. Emergy Evaluation of Water. University of Florida., Gainesville, FL.

Campbell, D.E., Garmestani, A.S., 2012. An energy systems view of sustainability: emergy evaluation of the San Luis Basin, Colorado. J. Environ. Manag. 95 (1), 72–97.

Carter, T., Keeler, A., 2008. Life-cycle cost-benefit analysis of extensive vegetated roof systems. J. Environ. Manag. 87 (4), 350–363.

Chang, N.B., Qi, C., Yang, Y.J., 2012. Optimal expansion of a drinking water infrastructure system with respect to carbon footprint, cost-effectiveness and water demand. J. Environ. Manag. 110C, 194–206.

Chapagain, A.K., Tickner, D., 2012. Water footprint: help or hindrance? Water Altern. 5 (3), 563–581.

Charles, K.J., 2009. Quantitative Microbial Risk Assessment: a Catchment Management Tool to Delineate Buffer Distances for On-Site Sewage Treatment and Disposal Systems in Sydney's Drinking Water Catchments. Doctor of Philosophy. University of New South Wales, Sydney, New South Wales, Australia.

Clark, C., Adriaens, P., Talbot, F., 2008. Green roof valuation: a probabilistic economic analysis of environmental benefits. Environ. Sci. Technol. 42 (6), 2155–2161.

Cochran, B., Logue, C., 2011. A watershed approach to improve water quality: case study of clean water services' Tualatin River program. J. Am. Water Resour. Assoc. 47 (1), 29–38.

Collier, S.A., Stockman, L.J., Hicks, L.A., Garrison, L.E., Zhou, F.J., Beach, M.J., 2012. Direct healthcare costs of selected diseases primarily or partially transmitted by water. Epidemiol. Infect. 140 (11), 2003–2013.

Cordell, D., Neset, T.S.S., 2014. Phosphorus vulnerability: a qualitative framework for assessing the vulnerability of national and regional food systems to the multi-dimensional stressors of phosphorus scarcity. Glob. Environ. Change 24 (1), 108–122.

Daily, G.C., Matson, P.A., 2008. Ecosystem services: from theory to implementation. Proc. Natl. Acad. Sci. 105 (28), 9455–9456.

De Gisi, S., Petta, L., Farina, R., De Feo, G., 2014. Using a new incentive mechanism to improve wastewater sector performance: the case study of Italy. J. Environ. Manag. 132, 94–106.

Dessai, S., Hulme, M., 2007. Assessing the robustness of adaptation decisions to climate change uncertainties: a case study on water resources management in the East of England. Glob. Environ. Change 17 (1), 59–72.

Dobbie, M.F., Brown, R.R., 2014. A framework for understanding risk perception, explored from the perspective of the water practitioner. Risk Anal. 34 (2), 294–308.

Dodds, W.K., Perkin, J.S., Gerken, J.E., 2013. Human impact on freshwater ecosystem services: a global perspective. Environ. Sci. Technol. 47 (16), 9061–9068.

Dwight, R.H.F., M, L., Bakerc, D.B., Semenzad, J.C., Olson, B.H., 2005. Estimating the economic burden from illnesses associated with recreational coastal water pollution—a case study in Orange County, California. J. Environ. Manag. 76, 95–103.

Fane, S.A., Ashbolt, N.J., White, S.B., 2002. Decentralised urban water reuse: the implications of system scale for cost and pathogen risk. Water Sci. Technol. 46 (6–7), 281–288.

Fann, N., Fulcher, C.M., Baker, K., 2013. The recent and future health Burden of air pollution apportioned across U.S. sectors. Environ. Sci. Technol. 47 (8), 3580–3589.

Folke, C., 2010. How Much Disturbance Can a System Withstand? with Roots in Ecology and Complexity Science, Resilience Theory Offers New Ways to Turn Crises into Catalysts for Innovation.

Fuentes, I., Rodriguez, M., Domingo, C.J., del Castinllo, F., Alvar, J., 1996. Urine sample used for congenital toxoplasmosis diagnosis by PCR. J. Clin. Microbiol. 34 (10), 2368–2371.

Gabe, J., Trowsdale, S., Vale, R., 2009. Achieving integrated urban water management: planning top-down or bottom-up? Water Sci. Technol. 59 (10), 1999–2008.

Ghimire, S.R., Watkins Jr., D.W., Li, K., 2012. Life cycle cost assessment of a rain water harvesting system for toilet flushing. Water Sci. Technol. Water Supply 12 (3), 309–320.

Haller, L., Hutton, G., Bartram, J., 2007. Estimating the costs and health benefits of water and sanitation improvements at global level. J. Water Health 5 (4), 467–480.

Hanafiah, M.M., Xenopoulos, M.A., Pfister, S., Leuven, R.S.E.W., Huijbregts, M.A.J., 2011. Charaterization factors for water consumption and greenhouse gas emissions based on freshwater fish species extinction. Environ. Sci. Technol. 45 (12), 5272–5278.

Hardisty, P.E., Sivapalan, M., Humphries, R., 2013. Determing a sustainable and economically optimal wastewater treatment and discharge strategy. J. Environ. Manag. 123, 98–104.

Havelaar, A., Melse, J.M., 2003. Quantifying Public Health Risk in the WHO Guidelines for Drinking-water Quality: a Burden of Disease Approach. RIVM raport 734301022. RIVM, Bilthoven.

Havelaar, A.H., De Hollander, A.E.M., Teunis, P.F.M., Evers, E.G., Van Kranen, H.J., Versteegh, J.F.M., Van Koten, J.E.M., Slob, W., 2000a. Balancing the risks and benefits of drinking water disinfection: disability adjusted life-years on the scale. Environ. Health Perspect. 108 (4), 315–321.

Havelaar, A.H., de Wit, M.A., van Koningsveld, R., van Kempen, E., 2000b. Health burden in the Netherlands due to infection with thermophilic *Campylobacter* spp. Epidemiol. Infect. 125, 505–522.

Hester, E.T., Little, J.C., 2013. Measuring environmental sustainability of water in watersheds. Environ. Sci. Technol. 47 (15), 8083–8090.

Hoekstra, A.Y., Hung, P.Q., 2002. Virtual Water Trade: a Quantification of Virtual Water Flows between Nations in Relation to International Crop Trade. UNESCO-IHE.

Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M., 2011. The Water Footprint Assessment Manual: Setting the Global Standard. Earthscan, London, UK.

Hofstetter, P., Hammitt, J.K., 2002. Selecting human health metrics for environmental decision-support tools. Risk Anal. 22 (5), 965–983.

Howard, G., Charles, K., Pond, K., Brookshaw, A., Hossain, R., Bartram, J., 2010. Securing 2020 vision for 2030: climate change and ensuring resilience in water and sanitation services. J. Water Clim. Change 1 (1), 2–16.

Howe, C.A., Butterworth, J., Smout, I.K., Duffy, A.M., Vairavamoorthy, K., 2011. Sustainable Water Management in Cities of the Future. Final Report of the SWITCH Project 2006–2011.

Hurlimann, A., Dolnicar, S., 2010. When public opposition defeats alternative water projects - the case of Toowoomba Australia. Water Res. 44 (1), 287–297.

Hwanga, H., Forrestera, A., Lanseya, K., 2013. Decentralized Water Reuse: Regional Water Supply System Resilience Benefits.

Igos, E., Benetto, E., Dalle, A., Tiruta-Barna, L., Baudin, I., Méry, Y., 2014. Life cycle assessment of water treatment: the role of infrastructure vs. operation at unit process level. J. Clean. Prod. 65, 424–431.

IPCC, 2012. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., Midgley, P.M. (Eds.), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Cambridge University Press, Cambridge.

Jones, M.P., Hunt, W.F., 2010. Performance of rainwater harvesting systems in the southeastern United States. Resources. Conserv. Recycl. 54 (10), 623–629.

Jongman, B., Ward, P.J., Aerts, J.C.J.H., 2012. Global exposure to river and coastal flooding: long term trends and changes. Glob. Environ. Change 22 (4), 823–835.

Kärrman, E., Malmqvist, P.A., McConville, J., Pettersson, F., Svensson, G., Wittgren, H.B., 2011. Application of the Urban Water Framework – Systems Analysis in Practice International Water Association. Stockholm, 22–25 May.

Katukiza, A.Y., Ronteltap, M., van der Steen, P., Foppen, J.W., Lens, P.N., 2014. Quantification of microbial risks to human health caused by waterborne viruses and bacteria in an urban slum. J. Appl. Microbiol. 116 (2), 447–463.

Kubiszewski, I., Costanza, R., Franco, C., Lawn, P., Talberth, J., Jackson, T., Aylmer, C., 2013. Beyond GDP: measuring and achieving global genuine progress. Ecol. Econ. 93 (1), 57–68.

Lederer, J., Rechberger, H., 2010. Comparative goal-oriented assessment of conventional and alternative sewage sludge treatment options. Waste Manag. 30 (6), 1043–1056.

Leung, H.W., Jin, L., Wei, S., Tsui, M.M., Zhou, B., Jiao, L., Cheung, P.C., Chun, Y.K., Murphy, M.B., Lam, P.K., 2013. Pharmaceuticals in tap water: human health risk assessment and proposed monitoring framework in china. Environ. Health Perspect. 121 (7), 839–846.

Lundie, S., Peters, G.M., Beavis, P.C., 2004. Life cycle assessment for sustainable metropolitan water systems planning. Environ. Sci. Technol. 38 (13), 3465–3473.

Lundie, S., Peters, G., Ashbolt, N., Lai, E., Livingston, D., 2006. A sustainability framework for the Australian water industry. Water, J. Aust. Water Assoc. 33 (11), 54–59.

Lundie, S., Ashbolt, N., Peters, G., Livingston, D., Lai, E., Kärrman, E., Blaikie, J., Anderson, J., 2008. Sustainability Framework. WSAA Occasional Paper No.17. PART a: Methodology for Evaluating the Overall Sustainability of Urban Water Systems. In: PART B: a Review Comparing the WSAA Sustainability Framework to the Gold Coast Waterfuture Process. Water Services Association of Australia, Melbourne.

Lundin, M., Bengtsson, M., Molander, S., 2000. Life cycle assessment of wastewater systems: Influence of system boundaries and scale on calculated environmental loads. Environ. Sci. Technol. 34 (1), 180–186.

Luthy, R.G., 2013. Design options for a more sustainable urban water environment. Environ. Sci. Technol. 47 (19), 10719–10720.

Lyons, E., Zhang, P., Benn, T., Sharif, F., Li, K., Crittenden, J., Costanza, M., 2009. Life cycle assessment of three water supply systems: importation, reclamation and desalination. Water Sci. Technol. 9 (4), 439–448.

Maheepala, S., Blackmore, J., Diaper, C., Moglia, M., Sharma, A., Kenway, S., 2010. Integrated Urban Water Management Planning Manual. Water Research Foundation, and Commonwealth Scientific Industrial and Research Organisation (CSIRO), Denver.

Malmqvist, P.A., Palmquist, H., 2005. Decision support tools for urban water and wastewater systems–focussing on hazardous flows assessment. Water Sci. Technol. 51 (8), 41–49.

Memon, F.A., Zheng, Z., Butler, D., Shirley-Smith, C., Lui, S., Makropoulos, C., Avery, L., 2007. Life cycle impact assessment of greywater recycling technologies for new developments. Environ. Monit. Assess. 129 (1–3), 27–35.

Mishan, E.J., 1978. Elements of Cost Benefit Analysis. George Allen & Unwin Ltd, London, United Kingdom.

Mo, W., Nasiri, F., Eckelman, M.J., Zhang, Q., Zimmerman, J.B., 2010. Measuring the embodied energy in drinking water supply systems: a case study in the Great Lakes region. Environ. Sci. Technol. 44 (24), 9516–9521.

Mo, W., Zhang, Q., Mihelcic, J.R., Hokanson, D.R., 2011. Embodied energy comparison of surface water and groundwater supply options. Water Res. 45 (17), 5577–5586.

Moore, J., Kissinger, M., Rees, W.E., 2013. An urban metabolism and ecological footprint assessment of Metro Vancouver. J. Environ. Manag. 124, 51–61.

Morales, M.A., Heaney, J.P., Friedman, K.R., Martin, J.M., 2013. Parcel-level model of water and energy end use: effects of indoor water conservation. J. Am. Water Works Assoc. 105 (9), E507–E516.

Murray, C.J., Acharya, A.K., 1997. Understanding DALYs (disability-adjusted life years). J. Health Econ. 16 (6), 703–730.

Nelson, M., 1998. Limestone wetland Mesocosm for Recycling Saline Wastewater in Coastal Yucatan, Mexico. University of Florida, Gainesville, FL.

NRC, 2009. Science and Decisions: Advancing Risk Assessment. National Academies Press, Washington, DC.

NRC, 2012. Water Reuse:Potential for Expanding the Nation's Water Supply through Reuse of Municipal Wastewater. National Academies Press, Washington, DC.

O'Rourke, T.D., 2007. Critical infrastructure, interdependencies, and resilience. Bridge-Washington National Academy of Engineering. Washingt. Acad. Eng. 37 (1), 22.

Odum, E.P., 1983. Basic Ecology. Saunders College Pub, Philadelphia.

Odum, H.T., 1996. Environmental Accounting. John Wiley & Sons, New York.

OECD, 2010. Sustainable Management of Water Resources in Agriculture. OECD Publishing, Paris.

OECD, 2011. An OECD Perspective. OECD. In: Benefits of Investing in Water and Sanitation. OECD Publishing, Paris.

Otterpohl, R., Braun, U., Oldenburg, M., 2003. Innovative technologies for decentralised water-, wastewater and biowaste management in urban and peri-urban areas. Water Sci. Technol. 48 (11–12), 23–32.

Pabi, S., Amarnath, A., Goldstein, R., 2013. Electricity Use and Management in the Municipal Water Supply and Wastewater Industries. Final Report. Electric Power Research Institute, Palo Alto, California.

Page, D., D, P., Toze, S., Bixio, D., Genthe, B., Jimenez Cisneros, B.E., Wintgens, T., 2010. Valuing the subsurface pathogen treatment barrier in water recycling via aquifers for drinking supplies. Water Res. 44 (6), 1841–1852.

Pahl-Wostl, C., Lebel, L., Knieper, C., Nikitina, E., 2012. From applying panaceas to mastering complexity: toward adaptive water governance in river basins. Environ. Sci. Policy 23 (1), 24–34.

Petterson, S., 2010. Development of a Software Tool for Undertaking Comparative Risk Assessment of DBPs and Pathogens in Drinking Water. European Environment Agency, Denmark.

Pfister, S., Ridoutt, B.G., 2013. Water footprint: pitfalls on common ground. Environ. Sci. Technol. 48 (1), 4–4.

Pfister, S., Koehler, A., Hellweg, S., 2009. assessing the environmental impacts of freshwater consumption in LCA. Environ. Sci. Technol. 43 (11), 4098–4104.

Remy, C., Jekel, M., 2008. Sustainable wastewater management: life cycle assessment of conventional and source-separating urban sanitation systems. Water Sci. Technol. 58 (8), 1555–1562.

Richardson, S.D., T, A.T., 2011. Water analysis: emerging contaminants and current issues. Environ. Sci. Technol. 83 (12), 4614–4648.

Romitelli, M.S., 1997. Energy Analysis of Watersheds. University of Florida, Gainsville, FL.

Schlüter, M., Pahl-Wostl, C., 2007. Mechanisms of resilience in common-pool resource management systems: an agent-based model of water use in a river basin. Ecol. Soc. 12 (2), 23.

Schoen, M.E., Ashbolt, N.J., 2010. Assessing pathogen risk to swimmers at non-sewage impacted recreational beaches. Environ. Sci. Technol. 44 (7), 2286–2291.

Short, M.D., Daikeler, A., Peters, G.M., Mann, K., Ashbolt, N.J., Stuetz, R.M., Peirson, W.L., 2014. Municipal gravity sewers: an unrecognised source of nitrous oxide. Sci. Total Environ. 468, 211–218.

Soller, J.A., Schoen, M.E., Bartrand, T., Ravenscroft, J.E., Ashbolt, N.J., 2010. Estimated human health risks from exposure to recreational waters impacted by human and non-human sources of faecal contamination. Water Res. 44 (16), 4674–4691.

Stenekes, N., Colebatch, H.K., Waite, T.D., Ashbolt, N.J., 2010. Risk and governance in water recycling: 'Public acceptance' revisited. Sci. Technol. Hum. Values 31 (2), 107–134.

Stockholm Resilience Center, 2007. Resilience Dictionary.

Stokes, J.R., Horvath, A., 2006. Life cycle energy assessment of alternative water supply systems. Int. J. Life Cycle Assess. 11 (5), 335–343.

Stokes, J.R., Horvath, A., 2009. Energy and air emission effects of water supply. Environ. Sci. Technol. 43 (8), 2680–2687.

Stokes, J.R., Horvath, A., Sturm, R., 2013. Water loss control using pressure management: life-cycle energy and air emission effects. Environ. Sci. Technol. 47 (19), 10771–10780.

Strengers, Y., Maller, C., 2012. Materialising energy and water resources in everyday practices: Insights for securing supply systems. Glob. Environ. Change 22 (3), 754–763.

Tangsubkul, N., Beavis, P., Moore, S.J., Lundie, S., Waite, T.D., 2005a. Life cycle assessment of water recyling technology. Water Resour. Mangement 19 (5), 521–537.

Tangsubkul, N., Moore, S., Waite, T.D., 2005b. Incorporating phosphorus management considerations into wastewater management practice. Environ. Sci. Policy 8 (1), 1–15.

Teunis, P.F.M., Xu, M., Fleming, K.K., Yang, J., Moe, C.L., LeChevallier, M.W., 2010. Enteric virus infection risk from intrusion of sewage into a drinking water distribution network. Environ. Sci. Technol. 44 (22), 8561–8566.

Thomas, J.S., Durham, B., 2003. Integrated Water Resource Management: looking at the whole picture. Desalination 156, 21–28.

Tidåker, P., 2003. Life Cycle Assessment of Grain Production Using Source-separated Human Urine and Mineral Fertiliser. Report 251. Swedish University of Agricultural Sciences, Department of Agricultural Engineering (SLU), Uppsala.

Tillman, A.-M., Svingby, M., Lundström, H., 1998. Life cycle assessment of municipal waste water systems. Int. J. Life Cycle Assess. 3 (3), 145–157.

US-EPA, 2002. The Clean Water and Drinking Water Infrastructure Gap Analysis. Office of Water, United States Environmental Protection Agency, Washington, DC.

US-EPA, 2008. Reducing Urban Heat Islands: Compendium of Strategies.

US-EPA, 2010. Guidelines for Preparing Economic Analyses. U.S. Environmental Protection Agency, National Center for Environmental Economics, Washington, DC (US Forest Service i-Tree ECO, U.S. Forest Service).

US-EPA, 2013a. Community-Based Water Resiliency (CBWR) Tool.

US-EPA, 2013b. Rivers and Streams Assessment 2008–2009, A Collaborative Survey. Office of Wetlands, Oceans and Watersheds. Office of Research and Development, Washington, DC. EPA/841/D-13/001.

Venkatesh, G., Brattebø, H., 2012. Assessment of environmental impacts of an aging and stagnating water supply pipeline network. J. Ind. Ecol. 16 (5), 722–734.

Wackernagel, M., Rees, W.E., 1996. Our Ecological Footprint - Reducing Human Impact on the Earth. New Society Publishers Gabriola Island.

Wang, S., 2014. Values of decentralized systems that avoid investments in idle capacity within the wastewater sector: a theoretical justification. J. Environ. Manag. 136 (c), 68–75.

Watanabe, M., 2014. Dynamic emergy accounting of water and carbon ecosystem services: a model to simulate the impacts of land-use change. Ecol. Model. 27 (1), 113–131.

Wenning, R.J., Apitz, S.E., 2012. Ecosystem services: protecting the commons. Integr. Environ. Assess. Manag. 8 (3), 395–396.

Westrell, T., Bergstedt, O., Stenstrom, T.A., Ashbolt, N.J., 2003. A theoretical approach to assess microbial risks due to failures in drinking water systems. Int. J. Environ. Health Res. 13 (2), 181–197.

Westrell, T., Schonning, C., Stenstrom, T.A., Ashbolt, N.J., 2004. QMRA (quantitative microbial risk assessment) and HACCP (hazard analysis and critical control points) for management of pathogens in wastewater and sewage sludge treatment and reuse. Water Sci. Technol. 50 (2), 23–30.

WHO, 2010. Vision 2030. The Resilience of Water Supply and Sanitation in the Face of Climate Change.

WHO, 2012. Un-water Global Analysis and Assessment of Sanitation and Drinking-water (GLAAS) 2012 Report: the Challenge of Extending and Sustaining Services. World Health Organization, Geneva.

Wiedmann, T., Minx, J., 2008. A definition of 'Carbon footprint'. In: Pertsova, C.C. (Ed.), Ecological Economics Research Trends. Nova Science Publishers, Hauppauge NY, USA.

William, P.F., Mciwem, B., 2009. Influence of anaerobic digestion on the carbon footprint of various sewage sludge treatment options. Water Environ. J. 23 (3), 170–179.

Winz, I., Brierley, G., Trowsdale, S., 2009. The use of system dynamics simulation in water resources management. Water Resour. Manag. 23 (9), 1301–1323.

Wong, T.H., Brown, R.R., 2009. The water sensitive city: principles for practice. Water Sci. Technol. 60 (3), 673–682.

Zarghami, M., Akbariyeh, S., 2012. System dynamics modeling for complex urban water systems: application to the city of Tabriz, Iran. Resour. Conserv. Recycl. 60 (1), 99–106.

Zeeman, G., Kujawa, K., de Mes, T., Hernandez, L., de Graaff, M., Abu-Ghunmi, L., Mels, A., Meulman, B., Temmink, H., Buisman, C., van Lier, J., Lettinga, G., 2008. Anaerobic treatment as a core technology for energy, nutrients and water recovery from source-separated domestic waste(water). Water Sci. Technol. 57 (8), 1207–1212.

Zeng, Z., Liu, J., Koeneman, P.H., Zarate, E., Hoekstra, A.Y., 2012. Assessing water footprint at river basin level: a case study for the Heihe River Basin in northwest China. Hydrol. Earth Syst. Sci. 16 (8), 2985–2994.