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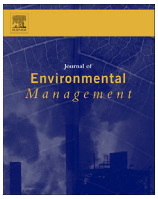

Research article

Influences of water quality and climate on the water-energy nexus: A spatial comparison of two water systems

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A B S T R A C T

As drinking water supply systems plan for sustainable management practices, impacts from future water quality and climate changes are a major concern. This study aims to understand the intraannual changes of energy consumption for water treatment, investigate the relative importance of water quality and climate indicators on energy consumption for water treatment, and predict the effects of climate change on the embodied energy of treated, potable water at two municipal drinking water systems located in the northeast and southeast US. To achieve this goal, a life cycle assessment was first performed to quantify the monthly energy consumption in the two drinking water systems. Regression and relative importance analyses were then performed between climate indicators, raw water quality indicators, and chemical and energy usages in the treatment processes to determine their correlations. These relationships were then used to project changes in embodied energy associated with the plants' processes, and the results were compared between the two regions. The projections of the southeastern US water plant were for an increase in energy demand resulted from an increase of treatment chemical usages. The northeastern US plant was projected to decrease its energy demand due to a reduced demand for heating the plant's infrastructure. The findings indicate that geographic location and treatment process may determine the way climate change affects drinking water systems.

1. Introduction

The prosperity of our society relies on a variety of highly interdependent infrastructure systems (e.g., water treatment and distribution, electricity grids, food production and supply network, etc.) working together without major interruptions (Konrad and Fuhrmann, 2013; Vespignani, 2010). Such interdependencies emerged along with the development of modern infrastructure. They can manifest as the functioning of one infrastructure relies on the functioning or resources provided by other infrastructures or when multiple infrastructures compete for the same resources. The water-energy nexus, for instance, has been widely recognized as a critical type of infrastructure interdependency that, if not understood and managed properly, could bring short and long term problems such as power plant shut downs due to water shortages and pollution (DOE, 2014), energy and financial stresses due to water pumping and treatment (Cherubini et al., 2009; Mo et al., 2016; Searchinger et al., 2008), as well as increased system vulnerability as a result of natural hazards, manmade threats (Hu et al., 2016), and climate change (Conway et al., 2015).

The degree and nature of infrastructure interdependencies continue to evolve under population, technology, climate, and policy changes. For instance, population growth could increase resource demand, and exacerbate the interdependency among their service infrastructures (Siddiqi and Anadon, 2011; Stillwell et al., 2011). Technology changes and utilization of unconventional resources (e.g., using desalinated seawater as a source of drinking water supply) sometimes also increase the degree of interdependency (Hussey and Pittock, 2012; Mo et al., 2014). Short and long term climate variabilities influence the quantity, and sometimes, the quality of available resources, as well as their societal demands, which further change the interdependencies among pertinent infrastructures (Delpla et al., 2009; Vörösmarty et al., 2000). Policies and regulations could have direct and indirect effects on all the aforementioned aspects (Romero-Lankao et al., 2017). Meanwhile, they can also be used as a means to

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guide the development of infrastructure and to reduce vulnerability resulting from infrastructure interdependency.

Recognition of the importance of infrastructure interdependencies, including the water-energy nexus, has motivated improved understanding of their dynamic complexity to inform future management decisions; yet our understanding of such dynamic changes is still very limited. Quantification of the water-energy nexus requires a comprehensive understanding of both direct and indirect (supply chain) interactions among the pertinent infrastructure. Life cycle assessment (LCA) has been a predominant tool used in previous studies for such quantifications as more data have become available. For example, the life cycle energy consumption of water supply, wastewater treatment (de Faria et al., 2015; Mo and Zhang, 2012), and water reclamation has been studied both separately and as a whole (Mo et al., 2014; Wakeel et al., 2016). Additionally, the life cycle water use of various types of energy supply has also been widely investigated. Nevertheless, most of these studies remain static and not suitable for predictions. Only a few efforts have been made to understand the future potential changes of the water-energy relationships from a life cycle perspective (Fulton and Cooley, 2015; Gerbens-Leenes et al., 2009), especially from the perspective of energy use by water supply. One study of a drinking water plant located in Florida reported that influent water quality could be responsible for about 14.5% of the changes of the plant's total operational embodied energy (Santana et al., 2014). Meanwhile, changes of water source mix combined with water demand growth have been found to significantly increase the electricity consumption of water supply, especially in coastal arid regions (Mo et al., 2014; Stokes-Draut et al., 2017). Efforts have also been made to project the future water-energy interdependence that could result from projected population growth, per capita water demand changes, preferred water supply options, and the required level of service (Hall et al., 2011; Lam et al., 2016). Very few studies have included climate variations in their future projections, and hence could only provide limited understanding of the influence of extreme climate events as well as gradual climate change on the water-energy nexus (Mo et al., 2016). The mechanism of how climate influences water treatment systems is still not well understood. Hence, empirical analysis based upon historical operational data have been suggested and applied (Mo et al., 2016; Santana et al., 2014).

While infrastructure interdependency is inherently complex, the current study adopts an empirical approach to investigate the temporal influences of climate, water quality, and water demand on the embodied energy of water supply. An assessment framework including life cycle energy assessment, regression analysis, relative importance analysis, and prediction analysis was applied. The influence of climate and water quality on the embodied energy of supply water from two surface water supply systems, each with distinct raw water quality, treatment processes, demand pattern, and local climate variations were investigated and compared. This study aims to assist proactive management of water and energy resources in different climates with the ultimate goal of improving the long term resiliency and sustainability of water and energy supply systems under global changes.

2. Methodology

2.1. Study site description

Two large-scale drinking water systems located in Tampa, FL and Boston, MA were selected for this study because coastal cities in the US are the most vulnerable to water supply and demand gaps; they represent two very different climates and have different source water quality (Oki and Kanae, 2006). The Tampa Water Treatment Plant (WTP) provides about 300 megalitre (ML) of water per day to approximately 588,000 customers in a service area of ~550 km^2. It relies on the Hillsborough River as the main water source, and employs a treatment process of rapid mixing, flocculation, sedimentation, pre-ozonation, biologically activated carbon (BAC) filtration, and disinfection to treat the water (Fig. 1). Ten types of chemicals are added at different points of the process: 1) sulfuric acid and ferric sulfate are added during rapid mixing for pH adjustment and coagulation, respectively; 2) dry polymer is added during flocculation for larger floc to form; 3) ozone is applied during pre-ozonation to destroy bacteria, viruses, pathogens, and taste- and odor-causing compounds; 4) hydrogen peroxide is used to remove ozone residuals; 5) lime is added to stabilize the pH of the water before it is filtered; 6) chlorine and ammonia are added together during the disinfection stage to form chloramine, a type of disinfectant that minimizes the formation of disinfection byproducts (DBPs); 7) sodium hydroxide is used for final pH adjustment; and, 8) fluoride is added for dental health benefits. Tampa Electric provides the facility with power, and the facility uses kerosene as backup energy. The Boston WTP, on the other hand, supplies around 750 ML of water per day serving 2.55 million customers in 48 communities in east and central MA (Mo et al., 2016). Water obtained from two adjacent reservoirs is used as the source water, and these reservoirs combined hold 1.8 trillion liters. Because of a relatively high raw water quality, the Boston WTP adopts a much simpler treatment chain of ozonation, chlorination, and final pH adjustment (Fig. 1; Mo et al., 2016). Seven types of chemicals are added for treatment: 1) liquid oxygen is used for ozone generation and the ozonation process; 2) sodium bisulfite is used for ozone removal; 3) sodium hypochlorite and ammonia are added to form chloramine for disinfection; 4) soda ash is added to raise the water alkalinity for pH buffering; 5) carbon dioxide is used for final pH adjustment; and 6) fluoride is used for dental protection. Furthermore, electricity and natural gas are used for pumping, treatment, and heating, and diesel is used as backup energy.

Tampa has a humid subtropical climate with strong alternating wet and dry seasonal cycles. The wet season, typically from June to September, has an average monthly rainfall of 17.7 cm, which is around two times higher than the rest of the year (5.86 cm) (Marda et al., 2008). The average monthly temperature in Tampa gets as high as 32.3 °C in July and August, and as low as 10.9 °C in January. Boston has a humid continental climate with mild summers and cold and snowy winters. Average monthly temperature varies from around 27.4 °C in July to around −5.4 °C in January. There is no significant intraannual precipitation variation in Boston. The highest amount of precipitation occurs in March (10.9 cm) and the lowest occurs in February (8.2 cm). Climate data of both WTPs were obtained from the National Oceanic and Atmospheric Administration (NOAA) National Climate Data Center, and the observation stations that are closest to the water sources were selected. Available climate data include monthly mean maximum temperature (T_{max}), monthly mean minimum temperature (T_{min}), monthly mean temperature (T_{mean}), and total precipitation amount for the month (P_{total}). Additionally, the greatest observed precipitation (P_{max}) and the monthly total snowfall (S_{total}) are available for the Tampa and Boston WTP, respectively. Air temperature influences water temperature and the amount of space heating and cooling. Precipitation and the associated runoff have a significant effect on water quality.

Twelve raw water quality indicators of the influent from the Tampa WTP are monitored on a daily basis: pH, color, $CaCO_3$ alkalinity, water temperature, specific conductance, threshold odor number (TON), iron, total organic carbon (TOC), specific ultraviolet absorbance (SUVA), turbidity, $CaCO_3$ hardness, and total coliform. Monthly data for these water quality indicators were obtained for a