Environmental Science and Pollution Research (2018) 25:33025–33037
https://doi.org/10.1007/s11356-017-0743-2

WATER, SANITATION, POLLUTION AND HEALTH IN THE ARCTIC

Applicability of energy-positive net-zero water management in Alaska: technology status and case study

Tingting Wu[1] · James D. Englehardt[2] · Tianjiao Guo[3] · Lucien Gassie[2] · Aaron Dotson[4]

Received: 15 January 2017 / Accepted: 14 November 2017 / Published online: 22 November 2017

Abstract

Challenges of water and wastewater management in Alaska include the potential need for above-grade and freeze-protected piping, high unit energy costs and, in many rural areas, low population density and median annual income. However, recently developed net-zero water (NZW), i.e., nearly closed-loop, direct potable water reuse systems, can retain the thermal energy in municipal wastewater, producing warm treated potable water without the need for substantial water re-heating, heat pumping or transfer, or additional energy conversion. Consequently, these systems are projected to be capable of saving more energy than they use in water treatment and conveyance, in the temperate USA. In this paper, NZW technology is reviewed in terms of potential applicability in Alaska by performing a hypothetical case study for the city of Fairbanks, Alaska. Results of this paper study indicate that in municipalities of Alaska with local engineering and road access, the use of NZW systems may provide an energy-efficient water service option. In particular, case study modeling suggests hot water energy savings are equivalent to five times the energy used for treatment, much greater savings than in mid-latitudes, due largely to the substantially higher energy needed for heating water from a conventional treatment system and lack of need for freeze-protected piping. Further study of the applicability of NZW technology in cold regions, with expanded evaluation in terms of system-wide lifecycle cost, is recommended.

Keywords Net-zero water · Energy-positive · Water management · Alaska · Water reuse

Introduction

Water management and energy management are two critical infrastructure pillars of the modern world, and the reciprocal relationship between the two is intensifying (Borrell 2015). For example, in urban areas, cities move over 130 billion gallons of water per day over distances of nearly 17,000 miles, population growth is increasing water demand, and global freshwater sources face threats to their quality due to industrialization, environmental deterioration, and climate change (Borrell 2015; Herman 2015; United Nations 2015). All of these factors increase the energy required for water management, while

---

Responsible editor: Philippe Garrigues

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11356-017-0743-2) contains supplementary material, which is available to authorized users.

✉ Tingting Wu
Tingting.Wu@uah.edu

✉ James D. Englehardt
jenglehardt@miami.edu

Tianjiao Guo
guoguo51988@gmail.com

Lucien Gassie
l.gassie@umiami.edu

Aaron Dotson
addotson@alaska.edu

[1] Department of Civil and Environmental Engineering, University of Alabama in Huntsville, 5000 Technology Drive, Huntsville, AL 35899, USA

[2] Department of Civil, Architectural, and Environmental Engineering, University of Miami, PO BOX 248294, Coral Gables, FL 33124-0630, USA

[3] Zhejiang JuNeng Co., Ltd., 1500 Daole Road, Tongxiang, Zhejiang 314500, China

[4] Department of Civil Engineering, University of Alaska Anchorage, 3211 Providence Drive, Anchorage, AK 99508, USA

increasing the major water withdrawals required for electric power production. In turn, the municipal water/wastewater sector consumes ~ 4% of US electricity, representing 1.6% of US total primary energy demand, 80% of which is required for conveyance (EPRI 2000). Moreover, another 3.6% of total US primary energy demand is used for heating of domestic and commercial hot water (U.S. Department of Energy 2015).

Challenges posed by management of the water-energy nexus are particularly acute in cold regions where communities may face unique vulnerabilities with respect to water supply (Alessa et al. 2008; Eichelberger 2010; Cozzetto et al. 2013). Although it is generally projected that freshwater availability may increase in the Arctic at the global scale as a result of increasing changes in the Arctic climate (Prowse et al. 2015; Bring et al. 2016; Lique et al. 2016; Vihma et al. 2016), the impact of such environmental change on water security is multifaceted and varying at the local scale, depending on the geographical area and the current state of infrastructure and industrial development (Alessa et al. 2008; Cozzetto et al. 2013). In particular, surface water sources and water supply infrastructure in Alaska are found to be dramatically affected by climate change (Alessa et al. 2008; Evengard et al. 2011; Cozzetto et al. 2013; Cochran et al. 2014). For example, permafrost degradation and erosion has caused increasing river turbidity and infrastructure damage (Durand et al. 2011; Brubaker et al. 2011a, b), and water levels in some traditional surface water sources decrease as permafrost degrades and the ground absorbs water (Yoshikawa and Hinzman 2003; Roach et al. 2011; Rover et al. 2012).

A reliable water supply becomes even more challenging in remote regions of Alaska, where remoteness of villages, high per-household costs, cultural miscommunication, high energy and transportation prices, subsistence level incomes, and difficult geographic and weather conditions including extreme cold, permafrost, and seasonally water quality variation may hinder access to water and sewer services (Smith et al. 1996; Eichelberger 2010). In particular, leakage (and/or "bleed") within the utilidor systems in northern Alaskan communities can sometimes account for the majority of water consumption (Smith et al. 1996). Small communities that rely on vehicle-hauled water delivery (i.e., small vehicle flush haul tanks and truck haul vacuum trucks), common in remote communities (from small communities with small truck haul systems such as Mycoreuk, AK to large communities practicing large truck haul such as Bethel, AK) must refill household storage tanks regularly and may have periods without water due to haul vehicle availability. Further, residents served by community piped systems also suffer water shortage or outage due to the increasing demand, lack of or reduced source water availability, or unanticipated well or distribution system freeze-up (Eichelberger 2010; Brubaker et al. 2011a, b). In many small (i.e., less than ~ 1000 people) remote villages (i.e., not connected to a road system), families may depend on a local washateria for purchase of treated potable water and access to basic facilities (i.e., laundry and showers). Conveyance of water and wastewater to a home in such situations may be by hand, due to the difficulty and expense of maintaining a pipe network or water/wastewater haul vehicles. As a result, all family members may wash their hands in the same bowl of water throughout the day, to conserve water, and may carry wastewater in a "honeybucket" (5-gallon bucket with a toilet seat) to a lagoon daily. Hence, it is not surprising that lack of in-home municipal water supply and sanitation in such villages has been linked with increased odds of acute gastrointestinal illness, and respiratory and skin infection rates (Gessner 2008; Hennessy et al. 2008; Thomas et al. 2016).

A dominant concern of utilities in Alaska is the need to prevent water from freezing during piped conveyance. While buried water and sewer lines are preferred for technical and aesthetic reasons, above-ground installation has often been necessary in Alaska with frozen soils (permafrost or a deep seasonal active layer). Further, utility burial in areas with frozen soil must consider availability and operation and maintenance costs of required excavation equipment (e.g., excavators, vacuum vehicles, and steam trucks) for maintenance. Permafrost degradation and changes in the seasonal active layer may lead to shifting and breakage of buried pipes, insulation, and recirculation systems (Smith et al. 1996). Methods to prevent pipe freeze include electric heat trace, alignment in utilidors that include warmer utilities, addition of propylene glycol to wastewater, and addition of heat to drinking water at the treatment plant. Infrastructure to protect the frozen soils (i.e., active cooling), and to prevent utility freezing, are often energy-intensive. Even in a large subarctic city such as Fairbanks, Alaska, electricity prices may be two or more times higher than in temperate regions (Electricity Local 2017).

Many approaches have been proposed to address challenges in water management, including large-scale rainwater harvesting, seawater desalination, and improved systems for water reuse, such as reusing wastewater for irrigation, and direct potable reuse of treated wastewater (Than 2011; Borrell 2015). More recently, net-zero water (NZW) systems have been proposed and implemented in a few applications (Harding 2009; Carter 2010; Bullitt Foundation 2013; Englehardt et al. 2013, 2016; Hickel et al. 2017). A NZW system is a water management system that neither imports nor exports significant water to or from the service area (Englehardt et al. 2013). It has also been defined as a system that limits consumption of freshwater resources and replenishes water to the watershed to avoid depletion of the water resources of a particular region (U.S. Army 2015).

Recently, a NZW system comprising a nearly closed-loop advanced oxidation-based direct potable water reuse system was designed and implemented at a University of Miami (UM) residence hall apartment. The system has been projected comparable in cost to conventional single-use technology (Guo et al. 2016), and capable of system-wide energy-positive operation through the retention of hot water thermal energy in the treated water. That is, by retaining ~85% of municipal water flow in the system, the thermal energy imparted by water heaters is retained in the water as well, so that the treated water returns to the tap warm and requires little re-heating. Thus energy is recovered without the losses associated with heat pumps, heat exchangers, or energy conversion, and hence more energy (water heater demand) can be saved than is used by the NZW system for treatment and conveyance (Gassie et al. 2016; Wu and Englehardt 2016). In addition, wastewater organics are mineralized to below 0.7 mg/L chemical oxygen demand (COD).

In this article, the potential implementation of an advanced oxidation-based NZW system is reviewed, as related to the challenges of water treatment and supply infrastructure in Alaska. In particular, data collected in the UM NZW project are reviewed and used to project potential capital and operating costs, and energy demand, as functions of treatment plant size. Then a hypothetical case study assessing energy and cost in the accessible and developed subarctic town, city of Fairbanks, AK, USA, is presented. Steady state water temperatures are modeled to assess the need for additional freeze protection infrastructure. Potential applicability of NZW technology in terms of projected energy savings as a result of the effective retention of wastewater thermal energy, operation and maintenance in Alaska, and associated cost implications are discussed. Detailed assessment of NZW energy and cost requirements for Fairbanks was not within the scope of this effort.

Current technology status of net-zero water management

Net-zero water management can include a broad range of systems, such as indirect potable reuse, septic tank/well, rainwater collection, and other systems that include onsite withdrawal and discharge. However, in urban areas of moderate precipitation, the population may be too large to support such systems, and substantial wastewater thermal energy is dissipated to the environment. Hence, to address water and energy concerns, direct potable reuse (DPR) may be considered. While some DPR plants are already in operation, none of those are considered NZW systems because only 20% of the wastewater is recycled, with the remainder drawn from environmental waters entering, in part, from outside of the service area (Englehardt et al. 2016). Ultimately, such systems dispose of most of the wastewater, precluding significant thermal energy retention. Also, most such systems utilize reverse osmosis (RO) technology to physically remove contaminants from the water by forcing water through a membrane under pressure. This process produces a reject stream of water that is concentrated with chemical contaminants and pathogens that requires separate disposal, often including additional treatment (Pérez-González et al. 2012). In addition, recovery rates of RO systems range from 40 to 90%, with energy costs rising exponentially as recovery rate approaches maximum (Dashtpour and Al-Zubaidy 2012; Altaee and Hilal 2015).

Advanced oxidation-based systems provide an alternative to RO-based reuse, which does not produce a concentrate stream potentially requiring further treatment and a disposal option that might be site-specific. Advanced oxidation processes (AOPs) rely on formation of hydroxyl radical, capable of mineralizing organic contaminants (Wu and Englehardt 2015; Gassie et al. 2016). Thus, most AOPs have good disinfection capability, and can further address the accumulation of chemicals in the global environment. For a DPR NZW plant, effluent requirements will be strict due to the source of the water. In particular, proposed DPR guidelines include 12-log inactivation of enteric viruses, with all regulated chemical contaminants below the Maximum Contaminant Level (MCL), and unregulated contaminants of concern, if present, removed during treatment (WateReuse Research Foundation et al. 2015). In addition, the treatment system must be robust and with contingency plans in place to ensure public health. As a gross measure of organic contaminants more representative of the degree of treatment, total organic carbon (TOC) has been proposed to be less than 0.5 mg/L, to ensure permanent destruction of emerging contaminants of concern (SWRCB 2015).

Historical implementations

Net-zero water treatment was first implemented for space travel, and in residential application by the Pure Cycle Corp. from 1976 to 1982. The former is located on the International Space Station, serving a crew of six with segregated, air-conveyed fecal disposal on earth, and rotary-vacuum distillation-based DPR of urine and cabin condensate (Carter 2010), at astronomical cost (Guo et al. 2014). Pure Cycle systems were installed in remote mountain locations without central water and wastewater services, monitored electronically, and maintained centrally by the company (Englehardt et al. 2013). These systems relied largely on ion exchange, generating a brine requiring disposal. While no longer offered or operated by the company, they would have retained thermal energy.

Pilot-scale NZW treatment system at UM, FL, USA

The UM NZW treatment plant was operated and studied for a period of 2 years (Englehardt et al. 2013; Wu and Englehardt 2015, 2016; Gassie et al. 2016; Guo et al. 2016). Multiple stages of treatment, ranging from anaerobic degradation in septic tank to advanced oxidation for organics mineralization, were utilized (Table 1). The design service flow rate was 400 GPD (gallon per day), with another 60 GPD (15%) of the treated potable discharged for irrigation, made up with 60 GPD from a rainwater cistern (sludge/residuals generation over the 2-year period of

Table 1 Treatment train of the UM NZW system

Stage	Process	Comments
1	Septic tank	2–3-day retention time for primary settling
2	Membrane bioreactor	Aerobic and anaerobic chambers, $CaCO_3$ and ethanol added for nutrient removal
3	Dosing tank	Flow equalization tank
4	Electrocoagulation	EC unit, aluminum electrodes used for bromate control, aeration for mineral precipitation. Dosing tank water blended with cistern water in this tank (85 to 15%)
5	Floc tank	Flocculation following EC, sludge pumped to septic tank
6	Vacuum ultrafilters	Membrane vacuum ultrafilters (VUFs), backwash delivered to septic tank
7	Clearwell	Flow equalization tank
8	AOP tanks	Advanced oxidation tanks, where process could be switched between ozone-hydrogen peroxide (peroxone, basis for energy-positive process) and UV-hydrogen peroxide (if needed to control bromate)
9	GAC filters	Central GAC filters were bypassed in favor of point-of-use GAC filters later in the project, but may be required for control of hydrogen peroxide residual in a system employing a UV-H_2O_2 AOP
10	Treated water tank	Tank for treated water storage and chlorine disinfection. Potable water overflow suitable for irrigation
11	Point of use GAC filters	GAC filters located on each sink and shower tap

operation was negligible). Wastewater from the apartment entered the 1195-gallon septic tank, where it underwent primary settling, anaerobic decomposition, and liquefaction for 2–3 days on average. Effluent flowed to a membrane bioreactor (MBR, Bio-Microbics, Inc., Shawnee, KS) where $CaCO_3$ and ethanol were fed to support biological nitrification/denitrification. MBR effluent passed to an in-house aerated aluminum electrocoagulation (EC), and vacuum ultrafilter (GE Power & Water, Ontario, Canada), to reduce dissolved solids and organics. From there, the water underwent treatment by advanced oxidation of residual total organics to below detection in terms of chemical oxygen demand (0.7 mg/L COD), by either UV-hydrogen peroxide or ozone-hydrogen peroxide (Spartan Environmental Technologies, Beachwood, OH). Finally, the effluent was chlorinated to provide disinfection residual, and passed through a GAC filter for redundancy. During the project, water was used by residents for all purposes except cooking and drinking (supplied from the grid as a precaution, due to the research nature of the project). Full system details are described elsewhere (Gassie et al. 2016; Wu and Englehardt 2016).

Project results were reported in previous studies over two phases (Gassie et al. 2016; Wu and Englehardt 2016) and summarized here (Table 2). Phase 1 of the project primarily involved the use of the peroxone AOP, iron electrocoagulation, and experiments with hydrogen peroxide disinfection prior to switching to chlorine, while in phase 2 the UV-H_2O_2 AOP was tested, and iron electrocoagulation was replaced with aluminum electrocoagulation, with and without aeration for enhanced mineral precipitation (Deng et al. 2013).

In terms of system design, AOP process selection involves trade-off between bromate generation, through reaction of with ozone with rainwater- and food-derived bromide, and energy consumption. For example, after 3.5 months of operation with peroxone, ~ 86 μg/L bromate was detected in the treated water, whereas, ~ 15 μg/L bromate was detected after 6 months of operation with UV-hydrogen peroxide (Gassie et al. 2016; Wu and Englehardt 2016). Hence, iron coagulation was replaced with aluminum, to remove bromide, and bromide was controlled with a dose of 15 mg Al/L (Gassie et al. 2016). However, during the entire 2-year period of operation, floc tank and VUF sludges were returned to the system septic tank, allowing accumulation of the bromide precursor. Also, note that UV-H_2O_2 consumed significantly more energy than the peroxone process (Table 2). Therefore, in a peroxone-based process, bromate was proposed to be controlled through aluminum electrocoagulation of bromide combined with disposal of EC backwash waters with 12% of the treated water (e.g., by reuse for irrigation, melting of snow, or other use external to the system) (Gassie et al. 2016).

In terms of disinfection capacity of the system, *Ct* values achieved were estimated based on the literature to be well over the 12 log virus inactivation guidelines set forth by the WateReuse Research Foundation for direct potable reuse (WateReuse Research Foundation et al. 2015). However, microbiological management proved challenging at times, presumably due to extremely intermittent and low flows in piping and tanks, dead zones in the AOP reactors and treated water tank designed and built in-house with off-the-shelf components, high water temperature, and lack of continuous chlorine monitor (Gassie et al. 2016; Wu and Englehardt 2016). Hence, automated chlorine control, with continuous mixing/circulation in small systems, is suggested. Also, based on our experience with the system using UV-hydrogen peroxide treatment, catalytic GAC filtration is recommended prior to

Table 2 Results of the UM NZW project

Parameter	Results
Phase 1 results (Wu and Englehardt 2016; Guo et al. 2016)	
Drinking water quality	115 of 115 drinking water standards met, with COD below detection (< 0.7 mg/L)
Emerging contaminants	97 of 97 selected hormones, pharmaceuticals, and personal care products were undetected in treated water
Recycle rate	Nearly closed-loop recycle rate of 85%, with replacement water from rainwater collected in a cistern. Steady state TDS was ~ 500 mg/L
Peroxone process	Peroxone AOP consumed 1.73–2.49 kWh/m^3 of treated water produced
Microbiological quality	No *Cryptosporidium* or *Giardia* detected; 8 of 136 daily fecal coliform measurements were positive. This latter result may be attributed to high water temperature, frequent access to the treated tank for research purposes, and periods of stagnation in piping influent to the treated water tank
Energy retention cost	Projected capability for energy-positive design and operation, due to retention of hot water energy in the system Total capital, operation, and maintenance cost (excluding land acquisition) of distributed implementation in Miami, FL, projected at $10.83/1000 gallon for a new system, 5% higher than the average current billing rate for water and sewer in the 50 largest US cities
Phase 2 results (Gassie et al. 2016)	
Drinking water quality	114 of 115 drinking water standards met (bromate exceeded), with COD below detection (< 0.7 mg/L)
Emerging contaminants	Of 1006 emerging contaminants analyzed, 56 were detected in MBR effluent, 50 were removed > 1 log, 3 were removed < 1 log, and 3 appeared to increase during treatment
Recycle rate	Nearly closed-loop recycle rate of 85%, with replacement water from rainwater collected in a cistern. Steady state TDS was ~ 500 mg/L, and ~ 575 mg/L when a 90% recycle rate was tested
UV-H_2O_2 process	UV-H_2O_2 AOP consumed 7.0 kWh/m^3 of treated water produced
Microbiological quality	No *Cryptosporidium*, *Giardia*, or coliphage detected in the treated water. Adenovirus was detected in some treated water samples, presumably non-infectious particles, or remnants of inactivated genomes
EC aeration	Aeration in the EC improved TDS reduction through the process from ~ 35 mg/L reduction to ~ 85 mg/L reduction, with calcium, magnesium, phosphate, and nitrate showing significant reduction of the selected analyzed minerals

chlorination, to quench residual H_2O_2 and avoid subsequent chlorine quenching.

Ultimately, results of the UM NZW project suggest that AOP-based NZW treatment can be cost-effective and energy-saving alternatives to other water management systems. Total operating and capital costs for a new distributed NZW system were projected at $10.83/1000 gallon, only 13% higher than projected costs for a new conventional system in Miami, FL (Guo et al. 2016), and 5% higher than average water and wastewater billing rates in the 50 largest US cities (Black and Veatch Corp. 2013). However, more experience with AOP-based NZW systems is needed, particularly in terms of long-term control of oxidative by-products and microbes.

Energy implications of NZW water management

One of the important drivers of the development and implementation of NZW management is the efficient retention of the thermal energy in wastewater, providing the opportunity for efficient energy recovery from wastewater. For example, a peroxone-based mineralizing NZW treatment system with a capacity of 1 million gallons per day (MGD) was projected to save more energy that would have otherwise been needed for heating water than was projected to be used in treatment and conveyance (Wu and Englehardt 2016). Note that these energy savings are realized outside the framework of water and wastewater service. Rather, these savings are passed on to the home or business owner in the form of a reduction in the energy used to heat water onsite (e.g., reduced use of electricity, natural gas, or diesel fuel), and associated cost.

Overview of water supply/wastewater treatment and potential advantages of net-zero water management in Alaska

Traditional water sources (e.g., surface water and groundwater) are present in most cold regions (Smith et al. 1996). While groundwater can serve as a source of supply in remote locations, extraction of groundwater in continuous and discontinuous permafrost regions can be expensive and water quality may be poor (i.e., highly mineralized and high concentration of dissolved organics). Therefore, surface water is commonly used as the water source for municipalities (Smith et al. 1996). However, surface water can suffer very low temperatures such that remote communities often need to heat their source water prior to treatment, then again during distribution, and then again within the home, and moving ice floes may damage water intake structures. Water quality may also be a concern because it may contain a high content of minerals and organic matter in summer and the freezing process concentrates these impurities in the remaining unfrozen water in winter (Smith et al. 1996).

In general, potable water for drinking and other human uses in Alaska may be acquired from either of two sources: traditional environmental water sources or a central water supply system. Residents in remote villages may prefer traditional water sources even when centralized water systems are available (Marino et al. 2009), for economic and/or cultural reasons. For centralized drinking water systems, water distribution may be realized via community-wide infrastructure, by vehicle delivery, or self-haul depending on local economic and environmental factors. Sewage lagoons, often biseasonally frozen, are the preferred wastewater treatment technology in many rural communities in Alaska, partly due to low operation and maintenance requirements and cost, with biological treatment occurring principally during the summer season. Wastewater is delivered via sewer pipe network, honey bucket haul, and vehicle-haul systems (Smith et al. 1996; Marino et al. 2009). Wetland treatment of wastewater was also reported to be feasible in North America and Scandinavia (Wittgren and Maehlum 1997).

Water/wastewater systems in Alaska are characterized by high construction and operation cost due to high energy and transportation cost, thermal design for freeze protection, remoteness of many communities, and unique hydraulic and structural features to accommodate the seasonally frozen soils (Smith et al. 1996). Moreover, low water temperature can affect properties of the water, and retard reaction rates and bacterial growth and activity, which may hamper water/wastewater treatment (Williamson 2010). Overall, access to treated water in Alaska rests on the affordability of the required energy for production, distribution, and consumption, which may be particularly low in remote areas due to the cost of fuel and/or electricity delivery through wilderness regions and a lack of employment opportunities. In fact, in rural small communities, ice and water may be collected as a traditional sustenance activity. Therefore, the delivery of improved sanitation and domestic access to potable water in Alaska, where needed, requires addressing the cost and availability of energy, as well as of water and even chemicals (Eichelberger 2010). As a result, a potentially energy-positive water management approach, such as advanced oxidation-based net-zero water treatment producing warm water, may represent an alternative to address water and energy issues (Table 3).

Case study of net-zero water treatment in Fairbanks, AK

The UM NZW technology discussed in this paper, while perhaps not generally applicable for residential use in remote areas with no road access and potential difficulties in providing maintenance service by trained professionals, may be appropriate in other areas. The city of Fairbanks, AK, was selected for a case study, to assess applicability and benefits of the technology particularly in terms of reduced energy demand and the potential to address the freezing of water in distribution networks. Reasons for selection of Fairbanks include its northern latitude, year-round road and air access for delivery of operation and maintenance items, access to engineering services, and water use typical of developed areas.

City overview

The total area of the city of Fairbanks, AK, proper is 32.7 square miles (85 km^2), with 31.9 square miles (83 km^2) of land and 0.8 square miles (2.1 km^2) of water. The city has a population of 31,535 and household number of 13,056 in 2010 (US census Bureau 2011), and falls between the categories of suburban/flat topography and rural/flat topography as defined previously (Guo and Englehardt 2015). The city, though northerly, is subarctic located south of the Arctic Circle in interior Alaska. Local weather is classified as continental subarctic with long cold winter, and short warm summer during which much of the annual rainfall occurs. Temperature averages − 12 °F (− 24 °C) in winter and 61 °F (16 °C) in summer (Fairbanks Fire Department 2014). Moreover, the lowest mean temperature in January and February can be as low as − 32 °F (− 36 °C) (The Alaska Climate Research Center 2017).

The city of Fairbanks and close-in sections of the greater Fairbanks community rely on the Golden Heart Utilities Water Treatment Plant for potable water. This plant produces 1.3 billion gallon of water annually pumping from four wells along the Chena River (Utility Services of Alaska 2017). Current treatment processes include chemical treatment with sodium hypochlorite, ferric sulfate, lime, and a polymer to remove iron and manganese; the water is then stored in a clearwell before distribution. The water distribution system, including a series of water mains usually made of cement-lined cast iron or plastic, pump and circulation stations, fire protection apparatus and valves, needs to be a circulating system with the water continually flowing inside the main to prevent freezing (Utility Services of Alaska 2017). The current wastewater collection system is comprised wastewater

Table 3 Water challenges vs. envisioned benefits of net-zero water management applied in Alaska

Water challenges in Alaska	Envisioned NZW benefits
• Limited storage and seasonal fluctuations in quantity and quality of traditional water sources; water shortage at local scale as a result of changing climate	• Stable, non-seasonal, freshwater supply
• Inadequate access to clean water and wastewater treatment especially in remote areas	• High quality water produced from engineered systems
• Need for external energy/heat to prevent freezing of pipes	• Effective retention of wastewater thermal energy
• Potential need for above-grade pipe installation	• Potential buried pipe installation, reducing energy losses
• Need to melt source water under certain circumstance	• Potential to eliminate need for source water melting
• Adverse effects of low temperature on treatment process kinetics	• Higher water temperature and increased biological and other treatment efficiency

collection system feeding into wastewater lift stations and entering Golden Heart Wastewater treatment plant at the terminus.

Central water service notwithstanding, many homes in the Fairbanks metro area are off-grid and, where affordable, on wells producing water contaminated with arsenic, iron, and other constituents, pointing to the need for grid expansion. Furthermore, most wastewater mains are constructed of wood stave pipe more than 50 years old, with high density polyethylene (HDPE) lining being used to rehabilitate these pipes for extended life (Utility Services of Alaska 2017), pointing to the potential for infrastructure modernization.

Conceptual design of net-zero water treatment

Because advanced oxidation-based net-zero water treatment is nearly closed-loop, and minerals are not substantially removed in treatment, a sink for excess minerals is needed. Previous study suggested that the discharge of ~ 15% treated water for irrigation, made up with a concomitant volume of rain or snowmelt water, should be sufficient to keep the total dissolved solids under ~ 500 mg/L (Wu and Englehardt 2016). The city of Fairbanks experiences a monthly average rainfall of 0.90 in. and a monthly snowfall of 5.18 in. (NOAA 2011). In addition, NOAA National Server Storm Laboratory (2016) suggests an average ratio of 1:13 in calculation of equivalent rainfall from snowfall (13 in. of snowfall equals 1 in. of rainfall). Here the required rainfall/snowfall collection area was estimated based on these data and the assumption of 15% of 65 gallons per capita per day residential flow. Results indicate that during most months at least 35 m^2 per capita of rainfall collection area, representing a total 1.1 km^2 for the city, would be required to supply 15% makeup water to a NZW system. This modest area is less than the existing surface water area, implying that additional water storage requirements to meet demand during the dry season would be minimal if any. Further, any energy required for melting of snow would be limited to a maximum of that required to supply 15% of the total demand. Without year-round outdoor irrigation, hypothetical uses of this treated water could include the melting of snow in winter, warming of makeup water using a heat exchanger, support of indoor hydroponic growing operations, provision of water at local watering points, and seasonally appropriate irrigation of outdoor agriculture.

A schematic of the assumed NZW treatment process is shown in Fig. 1. This treatment scheme was initially demonstrated over 2-year period as a pilot-scale (400 GPD) system located in Miami, FL, USA, with the exceptions that, in the demonstrated system, backwash waters were returned to the septic tank, iron electrocoagulation was used rather than aluminum, and bromate concentration in the treated water exceeded the US drinking water standard. The current adaptations are expected to address potential bromate accumulation. In a larger system, the septic tank would likely be replaced by primary settling and anaerobic sludge digestion with methane collection. It is also assumed for the current analysis that any melting of snow potentially needed to supply ~ 15% makeup water can be accomplished by heat exchange with the ~ 15% treated water discharged. Such specific design decisions would ultimately need to be evaluated, together with the potential effect of cold ambient water temperatures on the biological, physical, and chemical treatment processes involved, though the closed-loop nature of the NZW process insulates it substantially from such impact.

Population simulation and cost estimation

Costs for the assumed NZW system were projected preliminarily as relative values, i.e., as a comparison with generalized costs projected previously for typical conditions in the contiguous 48 US states. Generalized assumptions presented previously (Guo and Englehardt 2015) were used. In particular, assumptions as to the average number of persons per home, average per-person water usage (in turn related to energy demand and cost), and peak design flows are significantly influential to

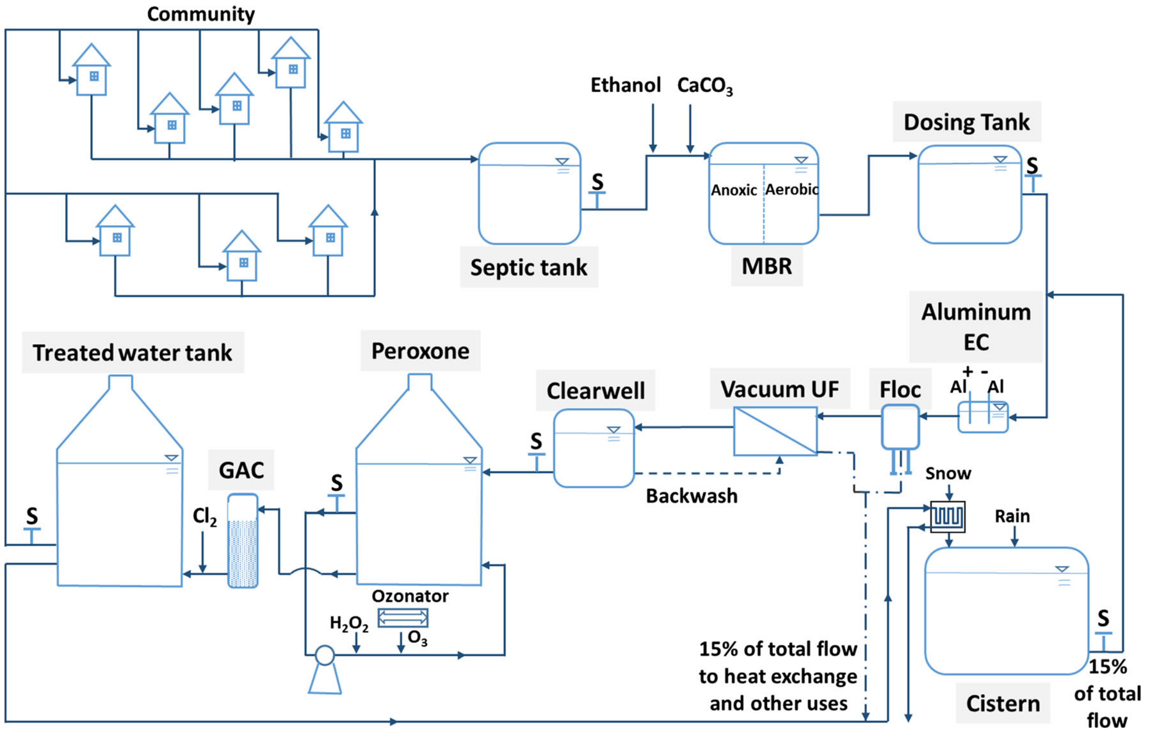

Fig. 1 Schematic of the proposed NZW treatment process [S; sampling ports]

the absolute costs obtained. In this work, overall flow per home was assumed at 187.5 gallon per home-day, with a peak flow of 2.6 for MBR, electrocoagulation, peroxone, and GAC sizing, though per-home flow may, for example, be comprised of a higher per-home population and lower per-person water usage. Four additional assumptions specific to Fairbanks were made as follows: (1) pipelines are buried underground with heavy insulation (R-60); (2) maximum temperature difference between the water and the ambient underground environment is 25 °C; (3) a construction cost factor of 1.9 is applied to all capital costs based on Smith et al. (1996); and (4) electricity rate is estimated at $0.24/kWh (Electricity Local 2017). All data analysis was conducted in Matlab® Software version 2015b.

To project NZW costs appropriate to the population distribution in Fairbanks, a simulation of the distribution of population across the area was performed based on US Census Bureau data (Fig. 2). The simulation process was similar to that reported in Guo et al. (2016) (Fig. 3). Given the irregular shape of the census blocks, a simplified procedure was used, as follows: (1) Population is read as a grayscale image, where the intensity of each pixel represents the population density; (2) the modified preferential growth model described in Guo and Englehardt (2015) is applied in a 10,000 m × 20,000 m parcel covering the entire city area, with the additional restriction that the simulated distribution of buildings corresponds to a population distribution not exceeding the local population density estimated in step (1); and (3) the number of buildings is then adjusted to match the actual household number, retaining the same distribution pattern generated from step (2). This procedure can quickly generate a rough digital characterization of the irregular geographical distribution of population in a city for planning purposes (Fig. 3).

Based on the simulated population distribution, the profile of total water capital, operating, and maintenance cost vs. number of treatment plants was then obtained following the hierarchical clustering process described in the model (Guo and Englehardt 2015). Capital includes treatment plant and distribution network, assuming new pipeline construction, O&M cost includes adjustment for administration. Savings accruing to the homeowner as a result of reduced energy for hot water, shown as a negative cost of water from a societal accounting stance, was estimated assuming a constant pipe radius and length representing averages during travel from the home to treatment and back. Treatment processes assumed to account for principal costs of treatment comprised MBR, electrocoagulation, ultrafiltration, peroxone, and GAC. Note that the relatively small cost of a second stage of ultrafiltration following EC was neglected, considering that the EC process might ultimately be integrated into the MBR process.

As shown in Fig. 4, the lowest projected total water cost, $53.71/1000 gallon, was obtained at approximately 3.3 plants per 1000 homes, equivalent to 306 homes per plant and 39 total plants (Fig. 4). Further, as the number of treatment plants decreases from 39 to 1, the total water cost per 1000 gallon increases slightly from $53.71 to $57.55 (7.1%), indicating flexibility in terms of the optimal capacities of treatment plants, allowing consideration of land use, rights-of-way, and other factors in water utility planning.

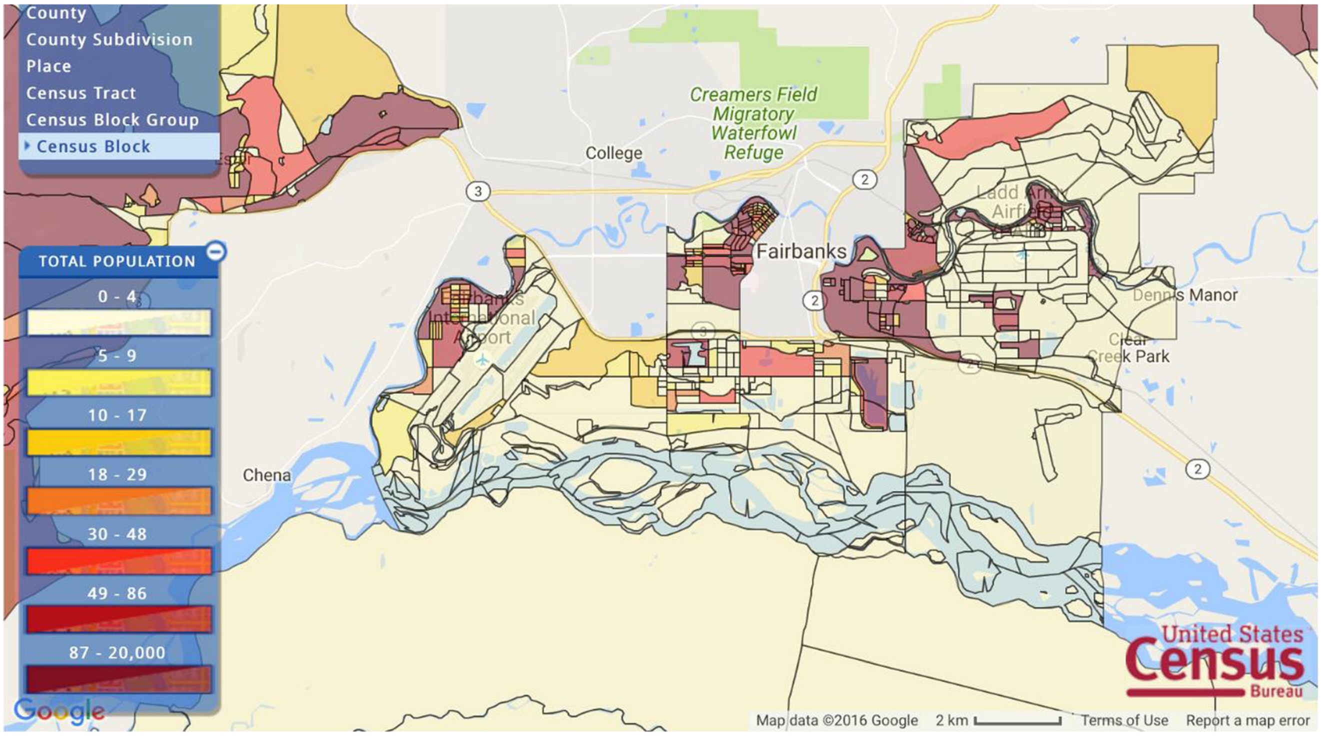

Fig. 2 Population of city of Fairbanks, 2010 (US Census Bureau 2011)

Energy projection

A preliminary heat balance analysis was conducted to project the steady state water temperature that might be expected in a (nearly closed-loop) NZW system of the UM design located in Fairbanks, and the resulting energy implications. In addition to projecting overall energy savings of such a system, this analysis projects the steady state

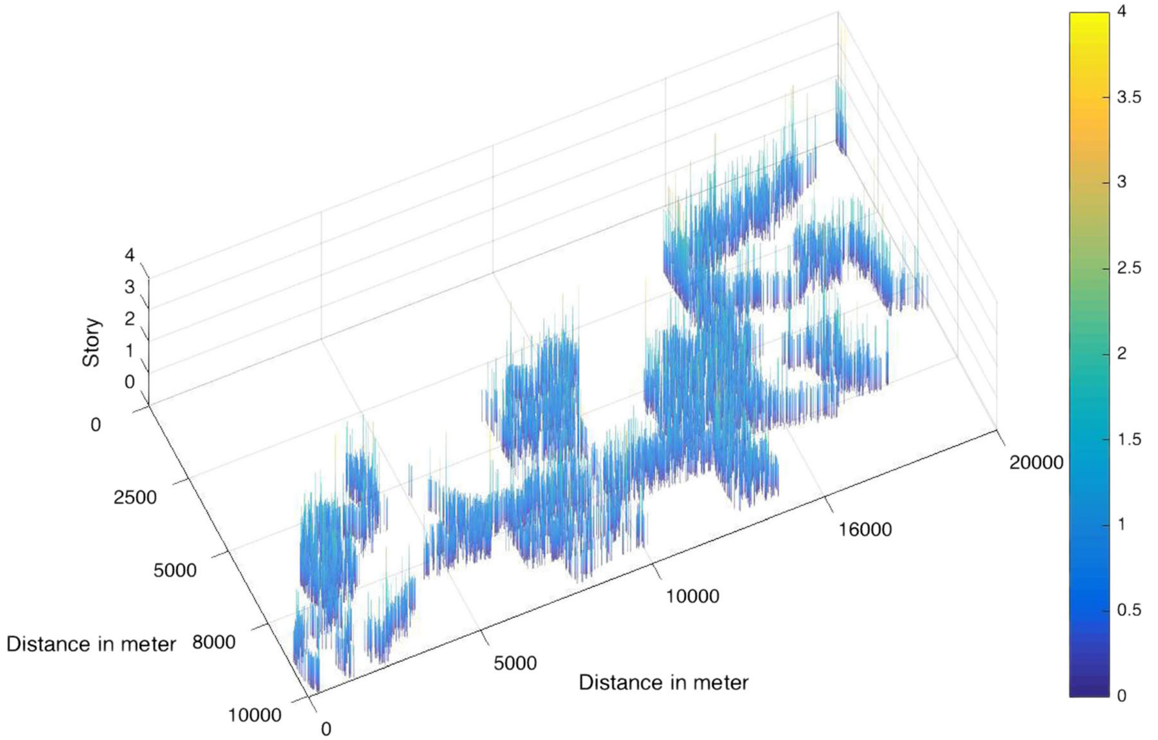

Fig. 3 Simulated population distribution of city of Fairbanks based on 2010 data (US Census Bureau 2011)

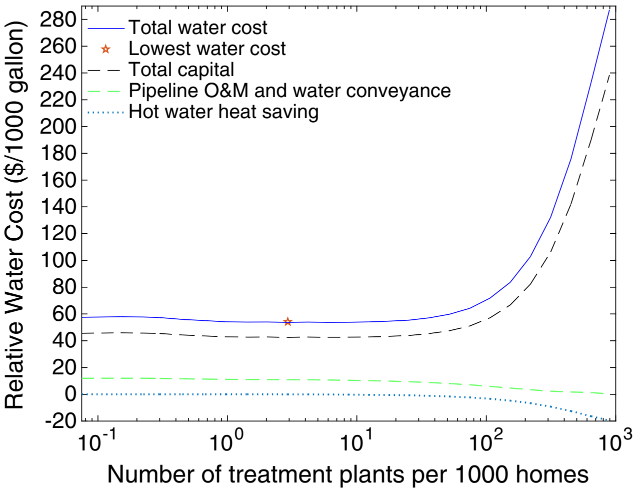

Fig. 4 Estimated NZW water cost vs. number of treatment plants [detailed cost information is available in Guo et al. (2014)]

temperature of the treated water as it re-enters the house, that is, at its lowest temperature following cooling in conveyance from house to plant, in treatment at the plant, and in conveyance back to the house. This minimum temperature in conveyance was important in determining whether NZW management can eliminate the need for community infrastructure freeze protection.

Although economic simulation results suggest that total water cost is slightly lower for NZW treatment plants sized to treat ~ 306 homes than for a plant sized to handle the entire population of the city of Fairbanks proper, energy demand per unit water produced increases significantly as plant size decreases. Therefore, the heat balance around the proposed NZW process was conducted assuming three plants, each 1.2 MGD in size (Table 4). The piping system was assumed to be buried underground with significant insulation (R-60). The existing drinking water and sewer collection systems are not suitable for the proposed system and complete system retrofit would be required prior to implementation of the NZW system. System-wide plumbing retrofit must also consider insulated access points (valves, hydrants, manholes, etc.) and avoid all cases of infiltration and inflow where near freezing groundwater could penetrate the sewage collection system. The ambient temperature for heat loss estimation during water/wastewater conveyance was assumed as 36 °F (2.2 °C) throughout the year (Strandberg 2017) assuming pipe is buried below frost depth and avoids installation in permafrost. Heat loss from heavily insulated treatment tanks (R-100) were assumed to be the same as above-ground systems where the ambient temperature was estimated to be 61 °F/16 °C (summer), − 12 °F/− 24 °C (winter), and − 45 °F/− 43 °C (extreme conditions). Details of the calculations follow those presented previously (Wu and Englehardt 2016), assuming *unit* costs for a 1.2 MGD plant are similar to those of a 1 MGD plant (EPRI 2000; Wu and Englehardt 2016) and adjusting ambient temperatures and energy required for residential hot water accordingly (Supplementary Information).

Table 4 Energy used and saved by 1.2 MGD NZW management systems in Fairbanks, AK

	Energy (kWh/m^3)		
	Summer[1]	Winter[2]	Minimum[3]
Treatment energy			
Advanced wastewater treatment[4]	− 0.78	− 0.78	− 0.78
Surface water treatment[5]	− 0.069	− 0.069	− 0.069
Peroxone mineralization[6]	− 2.11	− 2.11	− 2.11
H_2O_2 embodied energy[7]	− 0.021	− 0.021	− 0.021
Subtotal: energy for treatment	− 2.98	− 2.98	− 2.98
Hot water energy			
Hot water energy available to save[8]	25.73	25.73	25.73
Aeration heat loss[9]	− 2.22	− 4.16	− 4.87
Piping and tank heat losses[10]	− 0.74	− 0.75	− 0.76
Heat lost in use (shower)[11]	− 1.01	− 1.01	− 1.01
Heat lost in 15% irrigation water[12]	− 3.59	− 3.12	− 2.94
Subtotal: hot water energy saved	18.17	16.69	16.15
Net energy saved	15.19	13.57	13.17
Steady state tap water temperature (°C)	25.9	22.8	21.7

[1] Ambient temperature: 61 °F

[2] Ambient temperature: − 12 °F

[3] Ambient temperature: − 45 °F

[4] Pumping to treatment, bar screen, aerated grit chamber, diffused air aeration, nitrification, denitrification, chemical feed/mixing, filtration, primary sludge gravity thickening, secondary sludge flotation thickening, anaerobic digestion, belt press dewatering (EPRI 2000)

[5] Pumping to treatment, alum/polymer chemical feed, rapid mix, flocculation, sedimentation, filtration, chlorination, sludge drying beds, waste backwash water lagoon with pump to headworks (EPRI 2000)

[6] Electrical energy per order of magnitude COD mineralization in secondary effluent (EEO): 1.73~2.49 kWh/m^3 /log (Wu and Englehardt 2015)

[7] Gibbs Free Energy $H_2O + 0.5\ O_2 \rightarrow H_2O_2$ plus electricity-related losses, H_2O_2 dose 21.5 mg/L (Wu and Englehardt 2015)

[8] 2013 US average primary energy (fuel) use for residential and commercial, gas and electric hot water plus extra energy needed to heat up well water (36 °F in Fairbanks, AK; Strandberg 2017) to US average temperature (54 °F), assuming 283 L/cap·d (75 GPCD) average residential water use for new system with 15% outdoor use (Tchobanoglous et al. 2014; U.S. Department of Energy 2015)

[9] Method of Talati and Stenstrom (1990) assuming 99.3 m^3 air/m^3 water for diffused air aeration

[10] Includes heat loss from mains, laterals, and treatment tanks, relative to ambient temperature (36 °F for piping, 61 °F/− 12 °F/− 45 °F (summer/winter/min.) for tanks

[11] Based on 10 °F decrease, showerhead to drain, 11.7 GPCD average US shower use

[12] Based on 36 °F well water temperature (Strandberg 2017)

The NZW system (1.2 MGD) was projected to save 13.17~15.19 kWh/m^3 (Table 4), overall across wastewater and water treatment (accruing to the utility and potentially passed through to consumers), and hot water heating (accruing to homeowners directly). Moreover, minimum steady state water temperatures under all conditions evaluated are well above the freezing point even during the winter, indicating that no external heat would be needed to prevent freezing of pipes. Furthermore, at such water temperatures, possible adverse effects on treatment performance caused by otherwise low water temperature are presumably not a concern either. Significantly, even before considering energy saved due to lack of need for freeze prevention, savings in hot water heating energy exceed the energy required for treatment by factors of five to six. When coupled with the potential for freeze-free distribution without additional energy demand, the potential for more widely available piped water supply and wastewater treatment is suggested.

Conclusions and recommendations

The results of the initial case study presented here suggest that advanced oxidation-based NZW (nearly closed-loop) direct potable reuse systems, previously projected comparable in cost to conventional single-use water/wastewater technology, may offer some unique advantages in terms of managing the energy-water nexus in Alaska. While some assumptions made here, such as the specific AOP employed and the heat loss in collection/distribution and treatment, may affect the energy projection and require further study, the following conclusions may be drawn based on these initial results:

1. NZW systems can retain municipal water thermal energy, thus reducing the amount of energy required to heat residential and commercial water by an amount that may be equal to several times the amount of energy required for treatment;
2. Steady state water temperatures projected for the NZW system assumed for Fairbanks, AK, are well above freezing in both winter and summer, and extreme conditions, at plant scales of 1.2 MGD with highly insulated underground piping systems;
3. At the steady state water temperatures projected for the system described, continuous heat-add for water/wastewater distribution/collection and treatment by biological or chemical treatment are not required, although installation of freeze recovery systems are advised; and
4. The 15% of total treated water flow disposed by such a NZW system contains significant thermal energy that can be used to melt snow and/or warm the 15% makeup water. The cooled water may then subsequently have value in residential applications (e.g., water provision to local watering points) and commercial (e.g., indoor hydroponics).

Moreover, the energy projected to be saved by a NZW system in Fairbanks would have an economic value approximately double that of the same energy in the temperate USA. Hence, the approach may support extension of the water grid to more homes.

Potential advantages notwithstanding, the NZW technology examined would require local engineering and road access for operation and maintenance, and so may not be appropriate in remote areas. Also, energy aspects are strongly influenced by assumptions as to the AOP employed, which in turn may affect the potential long-term accumulation of bromate and other oxidative by-products in the treated water. Therefore, the following recommendations are made for the NZW technology:

1. NZW technology should be demonstrated further in terms of selection of AOP technology, and corresponding long-term control of microbial and chemical constituents; and
2. Regulatory agencies should develop mechanisms to support controlled demonstrations of NZW technology, with data collection and reporting.

More broadly, implementation of a community-wide technology like the proposed NZW system will require significantly greater evaluation of potential issues in Alaska and elsewhere:

1. As a retrofit, the NZW system described would require a complete community-wide piping upgrade, and associated evaluation of lifecycle cost and return on investment. Such investment may be appropriate in Alaska when infrastructure replacement is required due to age or need for below-grade network, and may also find application going forward in new developments and industrial installations such as mining camps;
2. While potentially beneficial in terms of treatment and energy conservation, maintenance of elevated temperatures in water and wastewater infrastructure in Alaska is known to be problematic. Greater consideration needs to be given to special tank venting that avoids icing and known infrastructure thermal bridges that would inadvertently cool the water or wastewater; and
3. To achieve the energy benefit projected, additional community-wide considerations would need to be in place to avoid inadvertent cooling of wastewater through discharge of large stored water amounts (e.g., pools or hot tubs) or wastewaters due to commercial or industrial activities (e.g., fish or game processing).

References

Alessa L, Kliskey A, Lammers R, Arp C, White D, Hinzman L, Busey R (2008) The arctic water resource vulnerability index: an integrated assessment tool for community resilience and vulnerability with respect to freshwater. Environ Manag 42(3):523–541. https://doi.org/10.1007/s00267-008-9152-0

Altaee A, Hilal N (2015) High recovery rate NF-FO-RO hybrid system for inland brackish water treatment. Desalination. Elsevier B.V., 363, pp. 19–25. https://doi.org/10.1016/j.desal.2014.12.017

Black & Veatch Corp (2013) 50 Largest cities water/wastewater rate survey. BLACK & VEATCH, Overland Park

Borrell B (2015) The urban water crisis

Bring A, Fedorova I, Dibike Y, Hinzman L, Mård J, Mernild SH, Prowse T, Semenova O, Stuefer SL, Woo MK (2016) Arctic terrestrial hydrology: a synthesis of processes, regional effects, and research challenges. J Geophys Res G: Biogeosci 121(3):621–649. https://doi.org/10.1002/2015JG003131

Brubaker M, Bell J, Berner J, Black M, Chavan R, Smith J, Warren J (2011a) Climate change in Noatak, Alaska, Strategies for Community Health. Available at: https://anthc.org/wp-content/uploads/2016/01/CCH_AR_062011_Climate-Change-in-Noatak.pdf

Brubaker M, Berner J, Chavan R, Warren J (2011b) Climate change and health effects in Northwest Alaska. Globle Health Action, 4(October). https://doi.org/10.3402/gha.v4i0.8445

Bullitt Foundation (2013) Bullitt Center: the greenest commercial building in the world. Available at: http://www.bullittcenter.org/. Accessed 20 July 2017

Carter L (2010) Status of the Regenerative ECLS Water Recovery System. AIAA Int Conf Environ Syst, Barcelona, p 1–11. https://doi.org/10.2514/6.2010-621

Cochran P, Huntington OH, Pungowiyi C, Tom S, Chapin FS, Huntington HP, Maynard NG, Trainor SF (2014) Indigenous frameworks for observing and responding to climate change in Alaska. Climate Change and Indigenous Peoples in the United States: Impacts, Experiences and Actions, pp. 49–59. https://doi.org/10.1007/978-3-319-05266-3_5

Cozzetto K, Chief K, Dittmer K, Brubaker M, Gough R, Souza K, Ettawageshik F, Wotkyns S, Opitz-Stapleton S, Duren S, Chavan P (2013) Climate change impacts on the water resources of American Indians and Alaska natives in the U.S. Clim Chang 120(3):569–584. https://doi.org/10.1007/s10584-013-0852-y

Dashtpour R, Al-Zubaidy SN (2012) Energy efficient reverse osmosis desalination process. Int J Environ Sci Dev 3(4):339–345 Available at: http://www.ijesd.org/papers/243-B20001.pdf

Deng Y, Englehardt JD, Abdul-Aziz S, Bataille T, Cueto J, De Leon O, Wright ME, Gardinali P, Narayanan A, Polar J, Tomoyuki S (2013) Ambient iron-mediated aeration (IMA) for water reuse. Water Res 47(2):850–858

Durand JR, Lusardi RA, Nover D, Suddeth R, Carmona-Catot G, Connell-Buck C, Gatzke S, Katz JVE, Mount JF, Moyle PB, Viers JH (2011) Environmental heterogeneity and community structure of the Kobuk River, Alaska, in response to climate change. Ecosphere 2:1–19. https://doi.org/10.1890/ES10-00111.1.

Eichelberger LP (2010) Living in utility scarcity: energy and water insecurity in Northwest Alaska. Am J Public Health 100(6):1010–1018. https://doi.org/10.2105/AJPH.2009.160846

Electricity Local (2017) Fairbanks electricity rates. Available at: http://www.electricitylocal.com/states/alaska/fairbanks/. Accessed 18 Aug 2017

Englehardt JD, Wu T, Tchobanoglous G (2013) Urban net-zero water treatment and mineralization: experiments, modeling and design. Water Res Elsevier Ltd 47(13):4680–4691. https://doi.org/10.1016/j.watres.2013.05.026

Englehardt JD, Wu T, Bloetscher F, Deng Y, du Pisani P, Eilert S, Elmir S, Guo T, Jacangelo J, LeChevallier M, Leverenz H, Mancha E, Plater-Zyberk E, Sheikh B, Steinle-Darling E, Tchobanoglous G (2016) Net-zero water management: achieving energy-positive municipal water supply. Environ Sci: Water Res Technol R Soc Chem 2(2):250–260. https://doi.org/10.1039/C5EW00204D.

EPRI (2000) Water and sustainability: U.S. electricity consumption for water supply &treatment—the next half century. Palo Alto, CA

Evengard B, Berner J, Brubaker M, Mulvad G, Revich B (2011) Climate change and water security with a focus on the Arctic. Glob Health Action 4(1):3–6. https://doi.org/10.3402/gha.v4i0.8449

Gassie LW, Englehardt JD, Wang J, Brinkman N, Garland J, Gardinali P, Guo T (2016) Urban net-zero water treatment: phase II field results and design recommendations. Water Res. Elsevier Ltd 105:496–506. https://doi.org/10.1016/j.watres.2016.09.005

Gessner BD (2008) Lack of piped water and sewage services is associated with pediatric lower respiratory tract infection in Alaska. J Pediatr 152(5):666–670. https://doi.org/10.1016/j.jpeds.2007.10.049

Guo T, Englehardt JD (2015) Principles for scaling of distributed direct potable water reuse systems: a modeling study. Water Res 75:146–163. https://doi.org/10.1016/j.watres.2015.02.033

Guo T, Englehardt J, Wu T (2014) Review of cost versus scale: water and wastewater treatment and reuse processes. Water Sci Technol 69(2):223–234 Available at: http://wst.iwaponline.com/content/69/2/223.abstract

Guo T, Englehardt JD, Fallon HJ (2016) Modeling the economic feasibility of large-scale net-zero water management: a case study. Water Environ Res 88(9):811–823. https://doi.org/10.2175/106143016X14609975747487

Harding M (2009) Personal communication. Pure Cycle Corp., Denver

Hennessy TW, Ritter T, Holman RC, Bruden DL, Yorita KL, Bulkow L, Cheek JE, Singleton RJ, Smith J (2008) The relationship between in-home water service and the risk of respiratory tract, skin, and gastrointestinal tract infections among rural Alaska Natives. Am J Public Health 98(11):2072–2078. https://doi.org/10.2105/AJPH.2007.115618

Herman M (2015) Thirsty yet? Eight cities that are improbably running out of water, takepart

Hickel KA, Dotson A, Thomas TK, Heavener M, Hébert J, Warren JA (2017) The search for an alternative to piped water and sewer systems in the Alaskan Arctic. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-017-8815-x

Lique C, Holland MM, Dibike YB, Lawrence DM, Screen JA (2016) Modeling the Arctic freshwater system and its integration in the global system: lessons learned and future challenges. J Geophys Res G: Biogeosci 121(3):540–566. https://doi.org/10.1002/2015JG003120

Marino E, White D, Schweitzer P, Chambers M, Wisniewski J (2009) Drinking water in northwestern Alaska: using or not using centralized water systems in two rural communities', Arctic. Arctic Institute of North America, 62(1), pp. 75–82. Available at: http://www.jstor.org/stable/40513266

NOAA, National Oceanic and Atmospheric Administration (2011) Fairbanks, Alaska A Climate Almanac. docs.lib.noaa.gov/noaa_documents/NOAA_related_docs/Fairbanls_Climate_Almanac.pdf. Accessed 20 Dec 2016

NOAA National Server Storms Laboratory (2016) Winter Weather FAQ. https://www.nssl.noaa.gov/education/svrwx101/winter/faq/. Accessed 30 Dec 2016

Pérez-González A, Urtiaga AM, Ibáñez R, Ortiz I (2012) State of the art and review on the treatment technologies of water reverse osmosis concentrates. Water Res 46(2):267–283. https://doi.org/10.1016/j.watres.2011.10.046

Prowse T, Bring A, Mård J, Carmack E (2015) Arctic freshwater synthesis: introduction. J Geophys Res G: Biogeosci 120(11):2121–2131. https://doi.org/10.1002/2015JG003127

Roach J, GRIFFITH B, VERBYLA D, JONES J (2011) Mechanisms influencing changes in lake area in Alaskan boreal forest. Glob Chang Biol. Blackwell Publishing Ltd 17(8):2567–2583. https://doi.org/10.1111/j.1365-2486.2011.02446.x

Rover JR, Ji L, Wylie BK, Tieszen LL (2012) Establishing water body areal extent trends in interior Alaska from multi-temporal Landsat data. Remote Sens Lett 3(7):595–604. https://doi.org/10.1080/01431161.2011.643507

Smith DW, Ryan WL, Christensen V, Crum J, Heinke GW (eds) (1996) Cold regions utilities monograph, 3rd edn. American Society of Civil Engineers, New York. https://doi.org/10.1061/9780784401927

Strandberg, Roy (2017) Personal communication, Engineer, Golden Heart Operations, Utility Services of Alaska, Inc., January 13.

Than, K. (2011) Could seawater solve the freshwater crisis?, National Geographic News

The Alaska Climate Research Center (2017) Available at: http://akclimate.org/Climate/Fairbanks. Accessed: 28 September 2017

Tchobanoglous G, Stensel HD, Tsuchihashi R, Burton F (2014) Wastewater engineering: Treatment and resource recovery, 5th Ed. McGraw-Hill, Inc., New York

Thomas TK, Hickel K, Heavener M (2016) Extreme water conservation in Alaska: limitations in access to water and consequences to health. Public Health 137(Supplement C):59–61. https://doi.org/10.1016/j.puhe.2016.06.002

U. S. Department of Energy (2015) Energy Information Administration. Available at: http://www.eia.gov/tools/faqs/faq.cfm?id=427&t=3. Accessed 1 Jan 2015

U.S. Army (2015) Army vision for net zero, Army Energy and Water Management Program

United Nations (2015) The United Nations world water development report 2015: water for a sustainable world. UNESCO, Paris

US Census Bureau (2011) Available at: https://www.census.gov/newsroom/releases/archives/american_community_survey_acs/cb12-175.html

Utility Services of Alaska (2017) Available at: http://www.akwater.com/water_treatment.shtml. Accessed 28 Sept 2017

Vihma T, Screen J, Tjernström M, Newton B, Zhang X, Popova V, Deser C, Holland M, Prowse T (2016) The atmospheric role in the Arctic water cycle: a review on processes, past and future changes, and their impacts. J Geophys Res G: Biogeosci 121(3):586–620. https://doi.org/10.1002/2015JG003132

WateReuse Research Foundation, American Water Works Association, Water Environment Federation, National Water Research Institute, Tchobanoglous G, Cotruvo J, Crook J, McDonald E, Olivieri A, Salveson A, Shane Trussell R (2015) In: Mosher JJ, Melin Varaniani G (eds) Framework for direct potable reuse. WateReuse Research Foundation, Alexandria

Williamson E (2010) Cold climate performance analysis of on-site domestic wastewater treatment systems. Water Environ Res 82(6):512–518. https://doi.org/10.2175/106143009X12529484815557

Wittgren H, Maehlum T (1997) Wastewater treatment wetlands in cold climates. Water Sci Technol 35(5):45–53 Available at: http://www.sciencedirect.com/science/article/pii/S0273122397000516

Wu T, Englehardt JD (2015) Peroxone mineralization of chemical oxygen demand for direct potable water reuse: kinetics and process control. Water Res. Elsevier Ltd 73:362–372. https://doi.org/10.1016/j.watres.2015.01.030

Wu T, Englehardt JD (2016) 'Mineralizing urban net-zero water treatment: field experience for energy-positive water management. Water Res. Elsevier Ltd 106:352–363. https://doi.org/10.1016/j.watres.2016.10.015

Yoshikawa K, Hinzman LD (2003) Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near council, Alaska. Permafr Periglac Process. John Wiley & Sons, Ltd 14(2):151–160. https://doi.org/10.1002/ppp.451