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Urban net-zero water treatment and mineralization: Experiments, modeling and design

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ABSTRACT

Water and wastewater treatment and conveyance account for approximately 4% of US electric consumption, with 80% used for conveyance. Net zero water (NZW) buildings would alleviate demands for a portion of this energy, for water, and for the treatment of drinking water for pesticides and toxic chemical releases in source water. However, domestic wastewater contains nitrogen loads much greater than urban/suburban ecosystems can typically absorb. The purpose of this work was to identify a first design of a denitrifying urban NZW treatment process, operating at ambient temperature and pressure and circum-neutral pH, and providing mineralization of pharmaceuticals (not easily regulated in terms of environmental half-life), based on laboratory tests and mass balance and kinetic modeling. The proposed treatment process is comprised of membrane bioreactor, iron-mediated aeration (IMA, reported previously), vacuum ultrafiltration, and peroxone advanced oxidation, with minor rainwater make-up and H_2O_2 disinfection residual. Similar to biological systems, minerals accumulate subject to precipitative removal by IMA, salt-free treatment, and minor dilution. Based on laboratory and modeling results, the system can produce potable water with moderate mineral content from commingled domestic wastewater and 10–20% rainwater make-up, under ambient conditions at individual buildings, while denitrifying and reducing chemical oxygen demand to below detection (<3 mg/L). While economics appear competitive, further development and study of steady-state concentrations and sludge management options are needed.

1. Introduction

The treatment of water to high purity at low energy is a challenge, if energy demands increase exponentially with treatment level, and energy demand is higher still for saline source water. A portion of this energy can be recovered from the wastewater, for example through the use of microbial fuel cells to generate electricity from the microbial oxidation of wastewater (Logan and Rabaey, 2012), or anaerobic treatment to recover methane (Tchobanoglous et al., 2003). In fact it has been estimated that chemical energy recovered from municipal wastewater might supply enough energy for treatment (McCarty et al., 2012). However, of the 4% of US electric power used for municipal water and wastewater management, the energy required for conveyance averages approximately four times that required for treatment (Cohen et al., 2004; ICF Consulting, 2002), much more than the available chemical energy. Also, while segregation of "grey water" from "black

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water" can allow treatment of this stream at lower energy in some applications, in centralized systems, the associated dual distribution system multiplies the cost of conveyance further.

Of note, treated municipal wastewater today represents a stable, non-seasonal, freshwater source meeting, for example, 87 of the 93 numerical drinking water standards on average across South Florida without further treatment (Bloetscher et al., 2005). Reuse of this water source could avoid the need for high-energy desalination, and water restrictions. As a result, the National Research Council has recently recommended general consideration of potable water reuse (NRC, 2012). Further, the report recommended consideration of potable water reuse without environmental buffer (PRWEB), also termed "direct potable reuse," due to lack of evidence that discharge to, and recovery from, an environmental water body enhances the quality of the treated water relative to other engineered reuse systems.

The concept of net-zero water (NZW) buildings, a term defined here to refer to building systems neither withdrawing nor releasing water off-site, offers several advantages. In addition to alleviating water rationing, the approach would address (a) the demand for conveyance energy, (b) current *de facto* reuse of wastewater-derived surface water, and (c) the need to treat for toxic chemical releases and pesticides, representing roughly 1 mg/L loading on U.S. surface and groundwater runoff. The latter approximation can be found by adding the total 2010 toxic chemical releases of 1.78 billion kg (U.S. Environmental Protection Agency, 2011) to the annual U.S. pesticide usage of 0.514 billion kg (Grube et al., 2011) and dividing by total U.S. surface and groundwater runoff of 6.8 billion m^3/d (van der Leeden et al., 1990). Moreover, with the principal toxic chemical load eliminated, treatment could focus instead on mineralizing pharmaceuticals and personal care products, which are not regulated in terms of environmental half-life as are other chemicals, thereby alleviating their associated endocrine-disrupting effects in the environment. Finally, a NZW system could efficiently retain thermal energy in the wastewater.

Net-zero water treatment was implemented successfully by the Pure Cycle Corp. from 1976 to 1982. These systems were installed in remote mountain locations without central water and wastewater services, monitored electronically, and maintained centrally by the company. Though Pure Cycle eventually exited the business due to the expense of maintaining systems across sparsely-populated mountainous regions, central systems across the same region would presumably have been more expensive. In testament to the success of the approach, many homeowners subsequently petitioned the state and obtained permits to continue operation independently (Harding, 2009).

Aside from psychological challenges to NZW living, several technological challenges need to be addressed. A potential challenge is management of the urban and suburban nitrogen balance. While many natural water and nutrient reuse options are viable in rural areas where most food is grown, most food is transported to urban/suburban areas, imparting a nitrogen load to wastewater far above drinking water standards and typically much more than can be absorbed by local vegetation. For example, three residents on a quarter-acre suburban lot produce ~13 lb N/1000 ft^2, roughly five times the amount of nitrogen that would be required for turfgrass fertilization across the property and roof. Hence, to avoid nitrate contamination of the groundwater, nitrogen must be returned either to rural areas or to the atmosphere.

Several approaches to the design of urban NZW systems can be considered. First, greywater and blackwater can be segregated, and this approach has advantage for residents interested e.g. in operating "dry" toilets to produce compost for onsite use. However, in general this approach requires homeowner operation of two multi-process treatment systems. Alternatively, infant drinking water could be segregated for additional treatment, potentially allowing the general nitrate drinking water standard (which guards against methemoglobinemia in infants) to be relaxed. However, such an approach would not address accumulation of nitrate in local groundwater. Similarly, drinking water could be segregated for additional treatment, though the concept further implies bathing and washing in non-potable water.

In contrast with segregation schemes, the seminal Pure Cycle system design of Howard Selby III relied on automated aerobic biological treatment, cloth filtration, ultrafiltration, deionization, and ultraviolet disinfection technology to treat commingled household wastewater (Selby, 1979). However, the system discharged nitrogen to the environment in concentrated brine, which today might also contain endocrine disrupting compounds (EDCs) including pharmaceuticals and personal care products. Also, the cost of acid and caustic regenerant may have been on the order of \$1.32/m^3 (\$5/1000 gal) treated water. In addition, the ultrafiltration membranes employed likely operated at pressures more than three times higher than ambient. Hence costs and energy may have been high as compared with natural biological systems that operate at nearly ambient temperature and pressure, and circum-neutral pH.

The purpose of the work reported in this paper is to identify a first design for an urban/suburban ambient net-zero water (UANZW) treatment process including mineralization of waterborne organics, and demonstrate the design versus laboratory and modeling results. Specifically, requirements were potable treatment, denitrification, and effluent mineralization of commingled domestic wastewater in individual buildings, at ambient temperature and pressure, and circum-neutral pH so as to minimize life-cycle energy. Recent membrane bioreactor, iron-mediated aeration (IMA, to be described), vacuum ultrafiltration, and peroxone advanced oxidation processes were tested and modeled, along with cistern make-up water and H_2O_2 disinfection residual. Because field data on steady state concentrations in such a closed-loop system were not found and cannot reasonably be simulated in a laboratory, the proposed system is under construction at a university residence hall for future demonstration. Modeling of the MBR biological treatment process, including nitrification/denitrification, is described elsewhere (Perera and Englehardt, 2012). Analysis of sludge management options and associated chemical/biochemical transformations is beyond the scope of the current project.

2. Materials and methods

The design of the proposed treatment system was based on preliminary laboratory screening of electrochemical, cloth