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Net-zero water management: achieving energy-positive municipal water supply

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Net-zero water (NZW) is a new vision for municipal water management, in which significant water is neither imported to, nor exported from the service area, *i.e.* local water independence. While such a system has long been possible in areas of sufficient water supply and/or sparse population, it is now becoming possible and economical for municipal systems in virtually any modern watershed, through the use of emerging direct potable reuse (DPR) technology. In fact, current implementations are producing design and operating data. Moreover, distributed NZW systems recycling at a high rate are projected to be capable of energy-positive operation, saving more domestic hot water energy than is consumed in treatment. However, NZW and DPR approaches vary widely in terms of source water, source segregation, treatment, and recycling rate. In this study, a workshop was convened to assemble and synthesize a broad cross-section of current NZW and DPR experience, to develop recommendations for water management planning. It was concluded that technology is currently emerging to support widespread NZW management. Recommendations included the introduction of NZW systems into new construction, to be supported by controlled demonstration projects over periods of two years or more; development of supporting regulatory structure with public engagement; development of real-time water quality monitoring devices; and re-tention of the term “net-zero water” to signify a new water management vision to advance water and energy autonomy.

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Water impact

Net-zero municipal water management, in which significant water is neither imported nor exported from the treatment plant service area, is now being shown capable of saving more energy (in domestic hot-water) than is used in treatment, through the use of emerging, economical direct potable water reuse technology to achieve high water and energy recycling rates.

Introduction

Current municipal water management often involves wholesale transfers of water among geographic areas, for single use and disposal, frequently to saltwater bodies or to freshwater sources. This reliance on conveyance and disposal evolved during times of small populations and limited water treatment capability, when basic sanitation and the protection of public health eclipsed the need for water and energy use efficiency. Today, more sustainable paradigms, such as *net-zero water* (NZW) management, are needed to address water shortages such as those that have plagued the Western US, and the energy demands deriving from conveyance of water and the disposal of wastewater containing domestic hot water thermal energy.

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A NZW system can be defined as a water and wastewater management system that neither withdraws nor releases significant flows of water outside of its service area, which area might range from a single residential lot to a large urban water district. NZW management implies that high-population, high-demand urban areas no longer consume water needed by downstream regions, nor depend on upstream regions for supply. In rural areas, for example, NZW management may involve simple harvest of rain or ground water, with reuse of wastewater and/or excess water for irrigation/aquifer recharge. More generally, municipal NZW management can now be realized in essentially any modern catchment basin, through use of direct potable reuse (DPR) water treatment systems. DPR systems are those in which recycled water is introduced directly into a potable water supply distribution system or into the raw water supply immediately upstream of a water treatment plant, without passage through an environmental buffer such as a reservoir or aquifer. Such systems have been shown capable of economically producing potable water from comingled municipal wastewater.^{1–4}

Motivations for net-zero municipal water management are compelling: in addition to avoidance of water shortages, it is now projected that a DPR NZW system can be significantly energy-positive, retaining and saving more hot-water thermal energy in the water than is used for treatment.⁵ In addition, available data indicate that water conveyance currently requires four times the energy required for treatment, on average in the US.^{6,7} Therefore, even without consideration of savings in residential hot water energy, a significant reduction in water conveyance energy (*e.g.*, pumping to/from central treatment) can be realized through the implementation of distributed systems. Further rationale for recycling water within the service area includes (a) use of treated municipal wastewater effluent meeting 87 of 93 numerical primary drinking water standards on average across South Florida without further treatment,⁸ and (b) avoidance of the disposal of such treated wastewater to open marine waters and similarly unconfined, saline groundwater aquifers so as to elevate the level of total impurities by a factor of ~ 100 .

Currently there are three known systems designed explicitly for NZW management, those being located on the International Space Station; at the Bullitt Center in Seattle, WA; and at the University of Miami (UM). The former serves a crew of six, with segregated, air-conveyed fecal disposal (on earth), and rotary-vacuum distillation-based DPR of urine and cabin condensate,⁹ at astronomical cost. The Bullitt Center system employs non-potable reuse (NPR) of greywater for irrigation, composting toilets, and rainwater harvesting for potable use.¹⁰ The UM NZW research and demonstration facility¹¹ is a DPR system serving a four-bedroom, four-bath residence hall apartment with biological treatment, aeration-precipitation/coagulation/filtration, and advanced oxidation treatment of comingled wastewater. Over 18 months of recycle operation, the plant converted nearly 100% of comingled apartment wastewater to drinking water, with discharge of 15% of the treated water (eventually to be used for irrigation),

and make-up with 15% rainwater, while mineralizing organics, including hormones, pharmaceuticals and personal care products, to below detection (0.7 mg L^{-1}) in terms of chemical oxygen demand. So far, compliance with all drinking water standards has been shown in short-term tests. Moreover, while the Bullitt Center potable use component awaits permitting, the other two systems have been successful in terms of consumer health.

Previously there have been two historical NZW implementations, as well as implicit examples. First, biological treatment/ion-exchange-based DPR systems were installed and maintained by the Pure Cycle Corp., for DPR treatment of comingled wastewater at single dwellings, from 1976 to 1982 in Colorado.¹² Second, in the Biosphere 2 closure experiment, eight researchers lived under a transparent $12\,700 \text{ m}^2$ (3.14 acre) dome containing an artificial ecosystem from 1991 to 1993, with air conditioning condensate supplying source water for drinking, and remaining wastewater being treated anaerobically for NPR as irrigation water.^{13,14} Finally, in rural areas where groundwater migration is minimal, septic tank/leachfield/well systems may be considered NZW management by indirect potable reuse (IPR), *i.e.*, by return of treated wastewater to an environmental buffer for subsequent potable reuse. All of these various NZW system types, when properly managed, have been successful in terms of public health,^{13,15} with Pure Cycle customers being given permission by the State of Colorado to continue operation independently after the company exited the business.

As illustrated by previous implementations, several approaches to NZW management present themselves, particularly in terms of the use of DPR, IPR, and NPR; of wastewater segregation or co-mingling; and of treatment technology. These approaches vary widely in terms of their ramifications for recovery of materials and energy, their costs, and their amenability to centralized regulatory oversight. Moreover, experience is becoming available with both DPR and NZW systems, which can provide basis for reconsideration of the structure and function of future municipal water and energy management systems, in light of current demands.

The purpose of this paper is to present a synthesis of current experience with NZW and DPR municipal water management, including a cohesive set of conclusions and recommendations as to how best to move forward in light of current challenges at the intersection of water and energy. To this end, a workshop was convened on May 29–30, 2014, at the University of Miami, Coral Gables, FL, with participation representing a broad spectrum of current expertise and experience regarding DPR and NZW systems. The state-of-knowledge was presented and discussed, including current experience with partial NZW ($<50\%$ recycle) public utility plants in Big Spring and Wichita Falls, TX, and Windhoek, Namibia; experience with the full NZW research installation at the University of Miami; and results of economic modeling studies and related projects. Four groups, each having representation across backgrounds and stakeholder groups, including academic and consulting engineers, equipment

manufacturers, regulators, architects, technology development investors, and public utility professionals (Appendix) were assembled to develop conclusions and recommendations. Group output, knowledge, and recommendations were then synthesized by participants with expertise in each of six topical areas, and assembled for review and revision by all participants. Discussion of systems relying on composting toilets was outside the scope of this work, due to current lack of acceptance of such systems in urban settings.¹⁶

State of technology

To date, considerable experience with NZW and DPR systems has been acquired, including an understanding of global drivers, an appreciation of regulatory issues, and recognition of the advantages of DPR in comparison with indirect water reuse (IPR).^{17,18} Advantages of IPR may include (a) elimination of the need for environmental buffer (potentially subject to site-specific catchment regulations and/or geological limitations), (b) decreased energy and costs of water conveyance and dual pipe installation, and (c) diversification of a utility's total water portfolio. However, needs are pressing for DPR-enabling legislation, and a clear and effective strategy for DPR implementation.

The practice of withdrawing water from inland areas, transporting it to urban population centers, treating it, using it once, and discharging it to the coastal waters, *e.g.* as currently practiced in California, Florida, and other coastal regions is now seen to be unsustainable. In contrast, the value of potable water, resources, and energy will propel municipal water management developments in the 21st century. As a result, future treatment plant design will need to consider modification of raw wastewater characteristics, flow equalization for improved process efficiency, elimination of untreated return flows, alternative end points for biological process design, and improvements in monitoring technology. One example is the success of the NPXpress® process¹⁹ in reducing energy requirements associated with nutrient reduction in biological wastewater treatment.

Water shortages in Namibia and Texas have already motivated the implementation of DPR plants, and experience is demonstrating success. In particular, the Goreangab DPR plant in Windhoek, Namibia,¹ was commissioned in 1968 and upgraded in 2002. This operating publically-owned water treatment plant has demonstrated success in reuse of *ca.* 20% of Windhoek wastewater while meeting water quality goals, addressing the severe lack of available freshwater in the arid region (Fig. 1).

In Texas, the stark difference between projected water demand in the year 2060 of $27.1 \times 10^9 \text{ m}^3$ (22.0 million ac-ft), and the corresponding projected water supply of $18.9 \times 10^9 \text{ m}^3$ (15.3 million ac-ft), has motivated public entities to implement alternative water supplies. According to the 2012 State Water Plan, reuse will account for about 10 percent ($1.23 \times 10^9 \text{ m}^3$ 915 600 ac-ft) of all new water supplies in 2060. In addition, the Texas Water Development Board has supported 14 water reuse



Fig. 1 The Goreangab DPR plant completed in 2002 in Windhoek, Namibia.

projects for total of US \$2 034 760 ; an operating emergency DPR plant in Wichita Falls (taken off-line July 2015); a project in El Paso currently involving pilot tests; and a proposed DPR plant in Brownwood (on hold). Moreover, a \$13 million biological/microfiltration/reverse osmosis/advanced oxidation-based DPR plant is already in operation in Big Spring, TX. Texas microbiological permit requirements are evaluated on a case-by-case basis, in terms of log-reductions from levels measured in treated wastewater effluent. For planning purposes, utilities assume 8- or 9-log virus, 6-log *Giardia*, and 5.5-log *Cryptosporidium* as the minimum inactivation requirements, with final requirements determined based on actual measurements of source water loading. These may be compared with requirements of the California Department of Public Health (now Division of Drinking Water), which require 12-log virus, 10-log *Giardia*, 10-log *Cryptosporidium* inactivation relative to the raw influent wastewater, and the recommendations of an independent expert panel convened for the WaterReuse Research Foundation, which proposes 12-log enteric virus, 10-log *Cryptosporidium* (*Giardia* implied), and 9-log bacteria inactivation, also relative to untreated wastewater.²⁰ Also of note is the water supply for the Solaire Building in New York City, which recycles up to $94.6 \text{ m}^3 \text{ d}^{-1}$ (25 000 gal d^{-1}) for toilet flush water, cooling tower make-up, and rooftop garden irrigation.

The UM research and demonstration project has included design, construction, and operation from January 2013 through December 2014 of a NZW DPR treatment system; study of psycho-social motivations for and against NZW living; and development of real-time water quality risk detection technology. Operating data on the system (Fig. 2) document the reduction in chemical oxygen demand to below the detection limit (0.7 mg L^{-1}), and reduction in nitrate/nitrite to below drinking water standards, with finished water turbidity and pH lower than county tap water, and a steady state value of $\sim 500 \text{ mg L}^{-1}$ total dissolved solids in the mineral water produced.⁵ Initial compliance with all Florida drinking water standards was shown in July 2014. Moreover, modeling studies indicated that (a) the cost of such a NZW system is



Fig. 2 The UM net-zero water treatment system, 85% recycle rate: (upper panel) below-grade septic tank, membrane bioreactor, and cistern, and (lower panel) UV-hydrogen peroxide advanced oxidation (aerated precipitation/aluminum electrocoagulation/vacuum ultrafiltration not shown).

already competitive with conventional water/wastewater technology,⁴ at plant sizes as small as 100 households per plant.³ Finally, it has so far been found that environmental and pro-science attitudes, risk-seeking, and past exposure to recycled water are negatively associated with disgust; disgust was the most important predictor of willingness to use recycled water; and participants given information about recycled water reported significantly lower disgust.²¹

Cost and energy footprint

The cost of NZW and DPR technology depends on the population density and the scale of the facilities involved. Generally an additional treatment stage, or advanced water treatment facility (AWTF), is needed, to serve as an additional treatment barrier and an added factor of safety for DPR. One example on which to base cost estimates for AWTFs with a capacity of at least 5 MGD is the Orange County Water District (OCWD) IPR system. This system includes water importation, and is therefore not NZW, but also includes injection

of treated wastewater to the primary water supply aquifer within the service area boundaries, following additional treatment by AWTF. Based on this experience, the addition of AWTF with RO would add a total of \$0.70–\$2.21 per m³ (\$2.65–\$8.36 per 1000 gal) to the cost of water and wastewater management, with higher costs driven primarily by the cost of concentrate management and conveyance.²²

For an advanced oxidation-based DPR plant, the principal additional treatment stage comprises advanced oxidation capable of mineralizing COD, *e.g.* to below typical detection limits (0.7 mg L⁻¹).^{1,5} For the peroxone advanced oxidation process, the additional cost for a 5 MGD plant has been estimated at \$1.15 per m³ (\$4.70 per 1000 gal), including annualized capital at 5% real interest (interest minus inflation), operation, and maintenance,²³ and costs for UV-hydrogen peroxide advanced oxidation may be similar.^{5,24} However, high recycling rates can be achieved with such systems and, as explained next, these costs may therefore be offset in distributed systems by up to \$1.70 per m³ (\$6.47 per 1000 gal) savings in energy to heat water (assuming an average US energy cost of \$0.12 per kW h). Moreover, chemical and microbial constituents are destroyed permanently, addressing environmental degradation in the vicinity of the service area.

Of note, a 2300 m³ d⁻¹ onsite DPR NZW system with insulated pipes achieving an 85% water recycling rate, possible *e.g.* in South Florida and whenever landscape irrigation requirements can be satisfied onsite, is projected in initial estimates to be capable of also recycling (retaining in the treated water) 69% of the energy required to provide hot water in buildings. In the US this savings may represent 14.2 kW h m⁻³ water service (7.1 kg CO_{2e} m⁻³), 60% more than the energy required to operate the NZW treatment system (assuming peroxone advanced oxidation with RO treatment of 15% rainwater makeup and anaerobic biological treatment; methane generation represents additional energy savings not accounted for here; RO- and peroxone-based systems with aerobic biological treatment are also projected capable of energy-positive operation). Accordingly, after accounting for the additional energy of treatment, such treatment systems are projected to have an energy footprint as negative as -4.0 kW h m⁻³ water service.⁵ In addition, distributed small-scale NZW plants require less energy for conveyance of water and wastewater and, as mentioned, US conveyance energy averages four times the energy of treatment. On the other hand, IPR systems and DPR systems achieving low recycling rates dissipate hot water thermal energy to the environment. In that case, the energy footprint of centralized systems having a capacity of 5 MGD or greater can be estimated to range from 0.86–1.06 kW h m⁻³ (3.25–4.00 kW h per 1000 gal, or 0.43–0.53 kg CO_{2e} m⁻³), based on experience with the OCWD RO-based AWTF.²²

Motivations and drivers

There is perhaps no more precious commodity than water, and while water is plentiful in many regions of the earth,

clean and energy-inexpensive water is not. Recent drivers of water shortage and increasing demands for clean water and energy include rapid population growth, industrialization, environmental deterioration, and climate change worldwide. Hence the grand challenge in terms of water: a new generation of sustainable water management in a resource-constrained world. NZW municipal water management represents a paradigm shift from centralized single use and disposal, to overall energy-positive water/wastewater treatment and energy-minimal conveyance. Additional drivers emerging as opportunities include recovery of nutrients; ecological and human health protection through the destruction of hormones, pharmaceuticals, personal care products, and other micro-constituents; and avoidance of the need to treat drinking water industrial hazardous waste releases, pesticides, and nitrate fertilizers. Also, the awareness that comes with the knowledge that household wastewater is recycled may impart a higher level of accountability for what is disposed to the drain.

In general, NZW can now be implemented in areas of high population density, *e.g.* high-rise buildings, and/or water of limited supply or poor water quality, and appropriately low-tech implementations are available for use in rural areas where water and nutrient recycling can be accomplished locally. Nonetheless, development and implementation of NZW treatment and management faces several challenges, including general principles and guidance for process design, current lack of regulatory structure and public acceptance, and a need for economic and performance data.

Conceptual system design

Fundamental goals inherent to the conceptual design of a NZW system are the reliable and resilient compliance with appropriately-high water quality standards, the satisfaction of quantity requirements for the intended use, and the attainment of these objectives at reasonable cost and with broad public acceptance. In that light, key questions were identified that can significantly influence design, including:

1) Is it imperative, for regulatory protection of public health, that recycled water meet all applicable drinking water standards at the point of plant discharge, or can point-of-use (POU) treatment systems, such as sink and shower filters, be considered to treat a small stream of water for drinking and bodily contact, alleviating the need to treat large volumes of water to drinking water standards?

2) Recognizing that an advanced oxidation-based plant design can allow a high degree of water recycling without generation of concentrate or brine,¹¹ is it imperative that organic compounds be mineralized in such systems to below detection in terms of chemical oxygen demand (COD) or total organic carbon (TOC)? Alternatively, what level of oxidation would ensure compliance with standards for disinfection byproducts, pesticides, and other emerging organics, while reducing system complexity and cost, particularly if improved monitoring technology is developed?

3) How can nitrogen and phosphorus be recovered from NZW systems, considering life-cycle and economic benefits and costs?

While further research is needed to address the questions just presented, principal findings regarding NZW system conceptual design can be summarized as follows. First, mass and energy balance analyses, more fundamental than are performed for design of conventional treatment technology, must be undertaken as the basis for NZW design. The mass component of the analysis must balance water, chemical additives, solids, contaminants, and nutrients. The energy component must balance principal demands including domestic hot water, pumping/conveyance, and aeration. Second, based on the mass and energy balances conducted, a design approach must be selected that involves either treatment of a comingled wastewater stream, or individual treatment of source-separated urine, fecal, and/or greywater streams. The latter approach, while perhaps more complex and energy-intensive in terms of material conveyance, particularly in distributed or centralized systems, is being studied as a way to facilitate nutrient recovery, because a majority of the nitrogen and phosphorus are contained in the urine while greywater accounts for the majority of the wastewater volume.

Following identification of the design approach, appropriate unit processes must be selected to address destruction, removal, and/or recovery of a suite of varied target constituents. Special attention must be paid to pathogen inactivation, along with the formation of disinfection byproducts (DBPs), the mitigation of emerging constituents such as pharmaceutical and personal products (PPCPs) and antibiotic resistance genes (ARGs), and the removal or recovery of nutrients. Further, aesthetic design and user integration play an essential role in a successful NZW project, particularly when a NZW system, including *e.g.* storage tanks, is integrated into a home. These aspects are tightly associated with public acceptance. Moreover, user-friendly operation and maintenance of a NZW system should be considered a part of the design process, as is expected in the design of other “home machines” including heating, ventilating, and air conditioning systems for which simple on/off control and periodic filter change may represent typical user requirements.

Two general approaches to conceptual NZW design were articulated, dependent upon the regulatory structure adopted. The first would be consistent with current regulations requiring treatment of all municipal treated water to meet all potable water standards. The second would assume two or more levels of treatment, *e.g.* separate standards for drinking and bathing water, and for other domestic water. This latter approach would allow for a higher and more energy-intensive and costly treatment of drinking and wash water, such as reverse osmosis or granular activated carbon. Also important to consider in the conceptual design phase is the development of improved failure response and monitoring systems. That is, the ultimate reliability of the conceptual design will result from the interaction of components of the design with monitoring and control elements. Finally,

rainwater storage and utilization is an important design consideration. In particular, appropriate water sources should be identified to compensate for water loss, however small, and to provide dilution. In fact, if adequate storage is available, rainwater supply may be a sufficient sole-source of water, and required treatment may be minimal.

Selection of unit treatment processes

In selecting NZW unit processes, system reliability is paramount, and therefore the use of redundant equipment to create multiple barriers to guard against the failure of individual components is important. Moreover, design must maximize such reliability while minimizing routine operation and maintenance, particularly in small and decentralized/distributed treatment plants. These competing objectives may be achieved through the incorporation of remote monitoring and process control systems, and provision of adequate equalization of the highly variable flows of water and individual constituents characteristic of small systems.

While many aspects of NZW unit process selection may be general, several site-specific aspects must be considered. First, the appropriate scale of treatment, whether on-site, distributed, or centralized, must be evaluated in terms of economics, energy, and life-cycle impacts. Currently little information is available on which to base these decisions. However, recent modeling studies indicate that on-site systems and plants serving <100 households are considerably more expensive in terms of total capital, operating, maintenance costs,³ than plants designed at larger scales. Very small treatment plants may also be larger in terms of plant footprint per unit of water produced, and may require automated monitoring and remote process control, for centralized oversight. However, plants serving 100–10 000 households were indicated to be lowest in cost, and such distributed systems are much smaller than are currently built in populated areas. Also, small systems are less energy intensive due to the ability to efficiently retain domestic hot water thermal energy in the treated water.

The rural or urban nature of the site is another important consideration. Rural systems may include below-grade anaerobic digesters, with gas collection to provide fuel *e.g.* for in-home lamps, and distribution of liquid effluent to agricultural plots for water and nutrient reuse; or in some cases simple sept tank/leachfield/well systems. In districts with sufficient rainfall and/or acceptance of compost toilets, a combination of rainfall harvesting and treatment, greywater recycling, and irrigation reuse, such as used at the Bullitt Center in Seattle, WA, may be employed for municipal water management.

In urban areas, consideration of the use of additional and/or higher-technology unit processes, and their interactions, may be required. Alternatives for treatment of raw wastewater include sedimentation, and aerobic and anaerobic biological treatment, with or without the integrated tertiary filtration of a membrane bioreactor. At this initial treatment stage, the

use of anoxic and anaerobic treatment processes can provide removal of a significant fraction of the biodegradable carbon with minimal energy and material input. Also, because wastewater typically contains much more nitrogen than can be absorbed by vegetation within the treatment plant service area, nitrogen removal from either comingled or source-separated wastewater, and from sludge, is important. Alternatives include conventional biological nitrification/denitrification (conversion of nitrogen species to nitrate and further to nitrogen gas for release to the atmosphere), and the anammox biological process,²⁵ which bypasses nitrification and therefore the typical need for alkalinity addition. However, production of nitrogen fertilizer from atmospheric nitrogen by the Haber–Bosch process is highly energy-intensive, and phosphorus is a non-renewable resource in limited supply. Moreover, while this nutrient load can be returned to agricultural areas for fertilization, return of the treatment sludge traditionally containing much of the nutrients may be energy-intensive or costly. Therefore, methods for the sustainable recovery of nutrients, through precipitation of struvite or otherwise, are needed.

Treatment to drinking water standards typically requires either reverse osmosis or advanced oxidation treatment. Reverse osmosis must be preceded by ultrafiltration or equivalent pretreatment, may require chemical addition to reduce fouling, and typically requires blending of product water to reduce corrosion. Moreover, concentrate representing perhaps 15–25% of the influent, depending on the process configuration, must be disposed of continuously. Partly as a result, recycling rates have been limited to less than 50%. Another alternative is the use of advanced oxidation to reduce organic constituents to an acceptable level (Englehardt *et al.* 2013). In particular, the UV-hydrogen peroxide process can mineralize organics without production of bromate, a byproduct of the oxidation of natural bromide in ozone-based processes, and aluminum coagulant can remove the bromide precursor. Alternatively, an ozone-based process such as ozone–hydrogen peroxide can be used, if a small RO unit is permitted for the point-of-use removal of bromate from a minor drinking/bathing-water stream.

The UM project demonstrated that conversion of 85% of the raw wastewater to potable water is possible, and projected that such advanced oxidation-based, non-RO systems can achieve significantly energy-positive operation by avoiding the discharge of hot water thermal energy to the environment. In particular, the addition of 15% rainwater, and disposal of 15% treated drinking water, was sufficient to result in a steady-state total dissolved solids value of $\sim 500 \text{ mg L}^{-1}$, relatively low for a mineral water (though high for a tap water). Thus a mineral water was produced, mimicking a living system. In such systems, the addition of minerals including metal salts for coagulation should be minimized. Therefore the UM system uses an aerated aluminum electrocoagulation process, termed aluminum-mediated aeration, to precipitate excess minerals, including bromide, and aid in low-energy vacuum ultrafiltration.

The management of process residuals is a final key consideration, particularly in the case of small NZW systems. In particular, reverse osmosis- and ion exchange-based systems produce a continual and significant stream of concentrate or brine, disposal of which may have environmental ramifications. In addition, a biological sludge, perhaps including trash screened from raw wastewater, undigested primary and secondary solids, and backwash water, is generated in all known systems which must be disposed occasionally. Disposal of any residuals to a centralized sewer would require maintenance of a separate centralized wastewater collection and treatment system, and therefore is not sustainable. In large systems, sludge disposal alternatives may include anaerobic digestion for recovery of methane and struvite. In on-site systems, sludge accumulated *e.g.* in a septic tank may require pumping and disposal every 1–2 years. Spent activated carbon and excess storm water may also require occasional disposal in some systems.

Operation, maintenance, and water quality monitoring

Superior process control, maintenance, and monitoring of NZW systems are critical to process reliability, in turn fundamental to public acceptance.²⁶ In that light, field and pilot tests of commercial equipment available for filtration, reverse osmosis, UV-hydrogen peroxide, and other treatment processes have demonstrated that quality equipment can produce high quality potable water from wastewater.^{27,28} Moreover, numerous indirect potable reuse (IPR) projects, including the long-term indirect potable reuse effort by the Orange County Water District²⁹ and several direct potable reuse programs, have confirmed that product water can exceed drinking water standards (in fact, as mentioned, RO product water is so devoid of contaminants as to be corrosive). In addition, the long-term reliability of DPR without RO has been demonstrated at the Windhoek plant.

Given the emerging nature of long-term experience, NZW projects may be permitted in the US only after formal operation and maintenance protocols are developed and documented. Operation and maintenance protocols are expected to include clear and detailed manuals, procedures, and supporting electronic databases, and schedules for routine replacement of chemical feeder pump elements, ultraviolet light bulbs, filter membranes, ozonator and oxygen concentrator parts, and other components of the system. Detailed plans will be required such that the failure of a pump, membrane, control system, or other electronic component can be managed without impacting system integrity or public health. The design life of some equipment may be effectively shortened to ensure protection of public health. Documentation of maintenance and replacement will be required as a part of routine regulatory reports, at least in the initial stages as facilities are brought on-line. In addition, regulatory agencies and the general public will expect ongoing, continual monitoring of equipment functions and water quality parameters.

Although electronic sensors are routinely used in water and wastewater treatment systems today, sensor reliability was recently identified as the principal current barrier to improving operational quality assurance.³⁰ Today such sensors send signals to programmable logic controllers (PLCs), to transmit data on to control systems and operations staff in large facilities. However, such systems will likely be required in NZW systems of all sizes, to monitor process performance and collect continuous water quality data for each process. In larger systems, sensor signals may provide input to SCADA systems that control the process and advise operations staff of issues requiring attention. As a result, the algorithms used by the control system to deal with process failures will become essential elements of a stable and reliable system. These algorithms will need to be refined with experience, and will be important considerations in terms of regulatory permitting.

Remote monitoring and control is expected to result in more reliable systems, because performance can be tracked through an analysis of trends in time series data. The use of cloud-based data management and control algorithms may further assist in the detection of process deviations, and allow a condition to be corrected in real-time before process failure occurs. However, sensor-based control systems will require operator expertise in computer programming and electrical component maintenance, at least until such systems are further developed. Moreover, because the scope of NZW treatment covers wastewater and drinking water treatment together, certification of utility operators in both subject areas will be important.

Risk management and regulation

Managing the risks of DPR and NZW technology will involve a combination of automatic, remote, and/or real-time process control and monitoring technology as just discussed, along with research and regulation. In that regard, continuing research is needed to better establish the efficiencies of removal, oxidation, and/or inactivation of fecal pathogens and organic constituents by advanced oxidation, membrane filtration, and other unit processes. Pathogens suggested for monitoring and control in current guidelines include virus, protozoan cysts and oocysts, and total coliform, and organics include perfluorooctanoic acid, perfluorooctane sulfonate, perchlorate, 1,4-dioxane, ethinyl estradiol, 17- β -estradiol, cotinine, primidone, phenytoin, meprobamate, atenolol, carbamazepine, estrone, sucralose, tris (2-carboxyethyl phosphine) hydrochloride, *n,n*-diethyl-metatoluamide, and triclosan.²² Such work can inform regulation, currently the principal impediment to technological development by industry.

While NZW and DPR systems are not as yet permitted in most areas of the US, extreme water scarcity is changing this situation in communities in California, Texas, and other areas of the US and the world, and these pressures are increasing with population pressures and the effects of global warming. From an engineering and water resources

perspective, IPR and DPR are considered viable options to increase water supply, with substantial environment benefits,³¹ and a reasonable record of research and field data supporting the fact that reliable technology exists. Nevertheless, valid public health and regulatory concerns will motivate regulations to ensure the appropriate application of NZW and DPR technology.

In Florida, for example, the Florida Department of Environmental Protection (FDEP) is responsible for administering water and wastewater programs, including water reuse, and while FDEP was not able to permit the UM experiment, the project was allowed for research purposes. According to FDEP, Florida encourages and promotes reuse of reclaimed water and water conservation. Sections 403.064 and 373.250 of the Florida Statutes establish the promotion and encouragement of reuse and water conservation as formal objectives, and state that reuse is in the public interest. FDEP rules and regulations on reuse and reclaimed water are contained in Florida Administrative Code Chapter 62-610, and Part V of which contains rules regarding IPR and groundwater recharge. Currently no Part V-reuse systems operate in Florida, though several proposed projects may be permitted in the near future.

The FDEP does not currently have rules regarding DPR; however, based on input received regarding Florida Senate Bill 536, the agency recognizes this lack of regulatory framework. The Department is therefore expected to begin the process of adopting rules to establish clear procedures and criteria for implementing DPR, considering both wastewater and drinking water aspects. In the case of on-site systems, rules will need to establish what party, homeowner or regulator, will be responsible for monitoring and compliance. This process will involve assembling a technical advisory committee to assist in developing rule revisions, utilizing DPR research conducted to date, and learning from the experience of other states such as Texas that have established regulations for DPR. Meanwhile, the Department will consider permitting of proposed projects on a case-by-case basis.

Clearly engineering, utility, regulatory, and academic stakeholder groups should work together from the start on development of integrated regulations addressing municipal water and wastewater management, including operator certification and training. In addition, standards developed should be adaptable to changes in technological capability. Controlled NZW and DPR demonstration projects should be permitted for the purpose of collecting data and providing basis of regulations to be developed. The safety of such projects can be ensured through the provision of remote monitoring programs.

While the purpose of the workshop was not to reach consensus on the details of NZW and DPR regulation, several specific suggestions were made for consideration in the process of developing regulations. First, in light of potential cost savings, it was suggested that consideration be given to the establishment of separate standards, and terminology, for (a) drinking water, and (b) water for other uses, to be termed

“purified” or “domestic” water. In that case, such “purified” water should be required to be free of acute risk, with less than a 10^{-5} risk of critical effect following one shower per day for 70 years. Further, it was suggested that a third category, intermediate to those for drinking and flushing, might also be considered for domestic washing and bathing. However, with technological improvements, such dual standards may become less important. It was also suggested that regulation of municipal water and wastewater management should be integrated, perhaps with regulation of power.

From the perspective of officials charged with protection of public health, the concept of DPR remains challenging. In fact, from this viewpoint, DPR may currently be considered for permitting by regulators only in cases of severe water shortage. In these cases, sophisticated engineering controls and real-time monitoring capability may be mandated, to increase the level of public health protection and address public confidence and acceptance. Even then, federal, state, and local regulatory communities may have legitimate concerns related, but not limited, to treatment process reliability and redundancy, monitoring requirements, and any proposed distinctions between potable and “purified” water. Only sustainable and targeted research and demonstration efforts can help reduce and/or eliminate these concerns, and provide basis for public outreach and acceptance.

Public acceptance

To achieve broad public acceptance, NZW management will require effective public education and transparent engagement. Fundamentally, these tasks will require the temporary but reasonably long-term permitting of public NZW and DPR demonstration projects, to include reporting and dissemination of monitoring results. More generally, consumer confidence in public water and power utilities is generally driven by several factors, including knowledge of associated constraints and needs; cost to consumers; concern for doing the right thing; the ‘cool factor’; and the self-protection instinct. In these regards, there is already a growing understanding of the limits to water supply. Hence, for example, water restrictions in Florida, California and elsewhere have been accepted by the public for several decades. In fact, in California, recycling of water for use in irrigation is already required for new construction in several districts,^{32,33} and is currently an essential aspect of new community planning.

Public acceptance of household or neighborhood water purification may follow the path of the growing acceptance of developments and homes that are off-the-energy-grid, *e.g.* through domestic solar and wind energy generation. In fact, there is a perceived demand to introduce NZW into such ‘green’ developments, as an ‘amenity’ like solar panels. Given that community-scale implementation may be more economically-attractive than on-site implementations, new community utility districts are already a vehicle for management of such small scale utilities. In fact, one can imagine eager acceptance of small-scale water provision and recycling

in underserved communities around the world. However, in the US and elsewhere, and similar to energy generation, equipment costs must be brought into line with customer ability- and willingness-to-pay, and the reliability of such systems must be established. Further, some provision should be made for local water supply in case of distributed system failure.

Unlike previous experience with the acceptance of off-grid energy, acceptance of off-grid water has historically been hindered by a disgust reaction sometimes called the 'yuck factor' experienced in some populations. This instinctual reaction can be answered through public education regarding the *de facto* water reuse that occurs in conventional systems through discharge of treated wastewater to water supply bodies. However, in light of this additional challenge, a more intimate model than distributed energy systems in terms of change in residential development might be the experience of the New Urban communities that are now thriving at twenty and thirty years old.^{34,35} In these communities, the utility of the automobile was intended to be replaced by alternate modes of mobility – transit, bicycling, walking – and this approach has resulted in enthusiastic acceptance, notably with the automobile not entirely removed but greatly reduced in use, through the availability of alternatives.

The path of acceptance of the New Urbanism, similar to that of reduced water consumption in Florida, followed a three-step development. First, the prospect of a changed environment was made appealing (in terms of the aforementioned drivers of change – knowledge, cost, ethics, the 'cool factor', and protection of self and family). The early New Urban communities such as Seaside, FL are beautiful and charming places that have enabled the public to experience a walkable daily life.³⁶ Second, the regulatory impediments were removed to enable early adopters to lead implementation and encourage development of the technology. Throughout the country, zoning codes had to be changed to allow the compact mixed-use walkable communities that were virtually out-lawed by the regulations. And third, with the growth of public acceptance through the experience of the first two steps, regulators were better prepared to make changes in standards. Now, there are jurisdictions with zoning codes that require all new community design to follow the principles of the New Urbanism.

Similarly to the acceptance of new-urbanist development, NZW supply might be first accepted by households and neighborhoods, when there is an informed consumer, when it is a choice that is made by the user, and when there is a fallback supply of conventional municipally treated water. Such an example, made appealing, can support the next steps of reducing regulatory impediments, and the eventual regulatory framework that requires the cycle of water-usage to be local and iterative. In fact, while regulators' response reflects prioritization of their responsibility for public safety, the response also reflects the state of public acceptance of potential change. This may vary by region; in Tampa, water produced by desalination is a long-accepted response to shortage, whereas in Miami-Dade County, discussion of alternate water sources is still nascent. It is worth noting that the

UM experiment produced a positive, and indeed enthusiastic, response by the students who chose to reside in the apartment using the system.

Conclusions and recommendations

The net-zero water concept presents a new vision for municipal water management which, while currently unique to a few implementations, is now becoming practical and technologically feasible for a wide variety of water reuse applications through the use of emerging DPR technologies. Motivations include step changes in the municipal demand for water and energy. In these regards, the University of Miami residence hall experiment/pilot project in particular may accomplish for DPR NZW projects what pilot programs of previous decades have achieved for other groundbreaking and innovative water reclamation and recycling concepts, including the indirect potable reuse "experimental" program in Orange County, CA, originally dubbed Water Factory 21. That is, the UM project has demonstrated the technical feasibility, economy, safety, and sustainability of urban, energy-positive, NZW management in the field. Even if funding is not continued, the project will have served further to show that this innovative water and energy recycling system can operate without routine discharge of residuals, while destroying endocrine-disrupting and other emerging organics in wastewater permanently.

Despite successes, current NZW implementations may not be easily duplicated in the near term, particularly outside of research and demonstration settings in which full disclosure and experimental protocol are subject to oversight. To move forward, policies, regulatory standards, and commercialized (*e.g.*, off-the-shelf) technologies are required to pave the way for wider adoption. While a regulatory structure will require time to develop, and this structure will be crucial to the development of cost-effective commercial equipment, nevertheless the value of water, and its perception among the general public, is increasing. As a result, public acceptance of potable reuse of all types is increasing along with its perceived inevitability. For example, the acceptance and enthusiasm displayed by students living in the Net Zero Water Project residence hall apartment is testament to the evolving acceptance of younger generations and the general public towards new technologies—even those providing such intimate and essential life-sustaining elements as water. In fact, society will demand this new technology, as drought, global climate change, and population growth, particularly in arid regions, drive water needs higher.

Several needs became clear in this work, and the following recommendations are made, in approximate order of chronological need:

1. Net-zero water systems should be distinguished from greywater systems and irrigation-based systems, by emphasizing the level of energy and water independence that can be achieved, without need for point-of-use treatment. Additional development of this approach in terms of reliability and monitoring features is suggested to achieve these goals in general practice;

2. Although, strictly, zero off-site water withdrawal and release may not be within reach in the foreseeable future, the term ‘Net-Zero Water’ should be retained to signify a goal, a vision, and a system that goes beyond previous water management systems in terms of water and energy autonomy;

3. Regulations should be developed in the short term to allow the construction and operation of NZW demonstration projects and direct potable reuse projects on appropriate scale, as a first step;

4. Support is needed for controlled NZW demonstration projects, operated in part to provide data and operating experience over periods of two years or more, to demonstrate long-term feasibility and provide basis for regulation of NZW and DPR in general. This work should include development of data on the cost and performance of non-reverse osmosis (e.g., advanced oxidation-based) treatment systems;

5. Research facilities capable of demonstrating energy-positive NZW technology, including the existing UM plant and others as they become available, should be supported and maintained for a period of years as regional test-beds for emerging technologies (nutrient recovery, emerging constituent and microbiological control, sensors, remote operation, automation, and alternative treatment technologies), to allow further process innovations, improvements and modifications;

6. Support should be found for the development of improved water quality monitoring devices, including devices capable of detecting potential microbiological and chemical health risk in drinking and other water in real time;

7. Research should also be supported regarding treatment process resiliency, system integrity, process monitoring and automation, fail safety, public education and community engagement, and the place of DPR in the wider context of Integrated Water Resources Management³⁷ and environmental sustainability, balancing concerns of utilities, regulators, and communities;

8. Ultimately, complete risk-based regulations should be developed, with fundamental consideration of regulatory structure including permitting of comingled and segregated streams; and

9. Along with pathways to permitting, marketing demonstration projects (builders’ shows, building managers conferences) are needed to educate and increase public acceptance, to allow advancement of the technology and associated safety aspects through evolving examples. Such an exposition of a likely future – the way solar collectors gained traction – perhaps coordinated by non-governmental organizations such as the WaterReuse Association and the National Water Research Institute, would thus advance water and energy goals without compromise in terms of public health.

Appendix

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