Review of cost versus scale: water and wastewater treatment and reuse processes

Tianjiao Guo, James Englehardt and Tingting Wu

ABSTRACT

The US National Research Council recently recommended direct potable water reuse (DPR), or potable water reuse without environmental buffer, for consideration to address US water demand. However, conveyance of wastewater and water to and from centralized treatment plants consumes on average four times the energy of treatment in the USA, and centralized DPR would further require upgradient distribution of treated water. Therefore, information on the cost of unit treatment processes potentially useful for DPR versus system capacity was reviewed, converted to constant 2012 US dollars, and synthesized in this work. A logarithmic variant of the Williams Law cost function was found applicable over orders of magnitude of system capacity, for the subject processes: activated sludge, membrane bioreactor, coagulation/flocculation, reverse osmosis, ultrafiltration, peroxone and granular activated carbon. Results are demonstrated versus 10 DPR case studies. Because economies of scale found for capital equipment are counterbalanced by distribution/collection network costs, further study of the optimal scale of distributed DPR systems is suggested.

Key words | distributed, optimization, reuse, scale, size, water

INTRODUCTION

US water/wastewater infrastructure is now aging and in need of repair or replacement, offering an opportunity for careful reassessment of the entire municipal water management system. In that light, a recent report by the US National Research Council (2011, p. 3) found that ‘The use of reclaimed water to augment potable water supplies has significant potential for helping to meet future needs …’ The report went on to note that, although de facto potable reuse, involving the use of source water largely composed of upstream wastewater effluent, is common in many US water systems, planned potable water reuse is not. Where practiced, potable water reuse has been termed either ‘indirect’ if treated wastewater is returned to the environment prior to reuse, or ‘direct’ if not. In fact globally there are currently no public water supplies utilizing more than 50% recycled wastewater. In that sense, all water reuse systems currently operating include an environmental buffer integral to the design. However, 100% direct potable water reuse (DPR), i.e. potable reuse without environmental buffer, was implemented successfully in Colorado from 1976 to 1982 (Selby & Pure Cycle Corp. 1979). Further, the National Research Council report found no evidence that an environmental buffer provides generally higher dilution and attenuation relative to an engineered system, and recommended that potable reuse with or without environmental buffer be considered as a water management alternative.

When considering DPR, distributed DPR systems may further be considered, given that centralized potable reuse systems with gravity collection would require upgradient distribution of treated water. In fact, even in centralized systems, the energy consumed for conveyance may be significantly greater than is used in the treatment process. According to Cohen et al. (2004) and Wolff et al. (2004), the energy cost per unit water supplied in California is approximately 20 times higher for conveyance than for treatment. In fact, in Iowa, energy consumed in conveyance of water/wastewater represents 30% of that consumed in treatment (Sauer & Kimber 2002). In another less extreme example, in Iowa, energy consumed in conveyance of water/wastewater represents 30% of that consumed in treatment (Sauer & Kimber 2002). In fact, a study supported by the Electric Power Research Institute concluded that roughly 4% of US electricity is used for...
treatment and conveyance of water/wastewater, of which 80% is used for conveyance (ICF Consulting 2002; Cohen et al. 2004). In addition, Cohen’s analysis indicated that at least 6% of the water is lost in centralized distribution systems, resulting in higher demands for both water and energy.

In addition to saving energy, distributed plants may be more resilient to willful attack, and amenable to technological evolution, allowing incremental technological changes to be implemented and tested when required by local conditions. Modern communications technologies also make it conceivable that many water/wastewater monitoring, operation, and maintenance functions can be decentralized, supporting savings in conveyance energy and water. In fact, small-scale treatment of black water in semi-public buildings has been predicted as a trend in the future based on projected savings in energy and water (Timmeren 2007).

In considering distributed DPR, the question arises as to the optimal scale of the individual treatment plants. In many cases this question would be addressed by attempting to minimize total cost, which might also tend to minimize life-cycle energy demand. However, information on the costs of water reuse processes as a function of process scale is inadequate, existing primarily in gray literature sources, limited by the current lack of potable water reuse design experience and the specificity of cost information to site characteristics, technological developments, and temporal and political variability in monetary values.

Traditionally, cost functions of the Williams Law form, 

\[ C = \beta \cdot Q^\alpha \]

in which \( C \) is cost, \( Q \) is system scale (size), and \( \beta \) and \( \alpha \) are positive constants (Williams 1947), have been found applicable for capital, operation and maintenance costs. The exponent \( \alpha \) is less than one when economies of scale obtain, and values ranging from 0.2 to 1.5 have been reported for many processes (Hinomoto 1974; Tyteca 1976; Gillot et al. 2007). Although economy of scale has generally been assumed for overall capital cost, diseconomy of scale has been reported for water treatment plant capital cost (Hinomoto 1974). Further, if energy costs for water/wastewater plants are assumed to follow Williams Law, and conveyance energy were constant at 80% of total energy as mentioned above, then total energy would be approximately 

\[ C = 5 \cdot \beta \cdot Q^\alpha \]

More realistically, the multiplier accounting for conveyance energy can be assumed a similar function of system size, equal to unity for a system serving a single building, so that 

\[ C = N^{\gamma} \cdot \beta \cdot Q^\alpha \]

in which \( N \) is the number of buildings served and \( \gamma \) is a constant. Then, the ratio, \( R \), of the cost of a single system serving \( N \) buildings to the cost of \( N \) systems serving \( N \) buildings is: 

\[ R = N^{\gamma} \cdot \beta \cdot Q^\alpha / N \cdot \beta \cdot (Q/N)^\alpha \]

At the break-even point for decentralization, this ratio is equal to unity. In that case, 

\[ N^{\gamma+\alpha-1} = 1, \text{ or in general } \gamma + \alpha = 1. \]

That is, for the centralized system to show advantage, the sum of the exponents must not exceed unity, even though the fraction of energy dedicated to conveyance may increase with system size (i.e. show diseconomy of scale, \( \gamma > 1 \)). Hence, diseconomy of scale may be more common than has been realized.

The purpose of this study is to review and synthesize available information on the costs of individual unit processes applicable for distributed DPR, as a function of process scale, and to verify this information as possible versus previous limited experience with DPR system implementation. In particular, a review is presented of cost information for unit processes useful for water reuse including activated sludge, membrane bioreactor (MBR), coagulation/foamulation, reverse osmosis (RO), ultrafiltration, perozone, and granular activated carbon (GAC), and continuous cost functions are developed. Review of costs for rainwater harvesting, which are highly site-specific, and other existing and emerging processes useful for reuse is beyond the scope of this study. Costs of previously reported reuse treatment systems are then estimated based on the cost functions presented, and compared to information available on actual system costs. Discussion and conclusions regarding DPR system costs are offered.

**COST FUNCTIONS FOR WATER REUSE UNIT PROCESSES**

In this section, cost information for several water/wastewater treatment and reuse unit processes is reviewed. To synthesize results for general applicability, reported results are first converted to constant 2012 US dollars in proportion to the increase in the GDP deflator (US Bureau of Economic Analysis 2013). Then, capital equipment and operation and maintenance (O & M) costs were fitted to functions of system scale including the form suggested by Williams (1947) using the Levenberg–Marquardt algorithm (Marquardt 1963) and SigmaPlot® version 12.0 software. The only function found to fit available cost data adequately over several orders of magnitude of system scale (including onsite systems) was a logarithmic variant of Williams’ power law, as follows:

\[ \log(y) = a[\log(x)]^b + c \]  

(1)

The \( R^2 \) values found for Equation (1) by non-linear regression are reported for each technology.
Activated sludge

The activated sludge process may be a useful DPR component for removal of organic and nitrogen constituents. Per capita capital cost was reported by Butts & Evans (1970) as a function of population served, with costs for factory-built package plants (750 to 5,000 people) and plants fabricated onsite (10,000 to 50,000 people) reported separately. In addition, costs obtained in current research, development, and construction of an onsite DPR system (Englehardt et al. 2013) indicate capital costs of $49,600 (2009) and $36,534 (2011) for 5.68 m³/d (1,500 US gallons per day (GPD)) and 1.89 m³/d (500 GPD) attached-growth biological treatment systems, respectively. In Figure 1, Equation (1) is fitted to the onsite data points and the capital costs obtained from the functions of Butts & Evans (1970) for package and site-built plants of selected capacities of 283.9, 733.0, 1,892.5, 3,785.0, 8,463.5, and 18,925 m³/d, assuming an average flow per capita as 0.378 m³/d (100 GPD) at capacities of 750, $\sqrt{750}=5,000$, 5,000, 10,000, $\sqrt{10,000}=50,000$, 50,000 people, with $R^2$ value of 0.999. Also shown is a line corresponding to a linear relationship between cost and capacity, i.e. neither economy nor diseconomy of scale, passing through the data point for the smallest plant. Economy of scale is indicated in this case, by a flatter empirical slope relative to the dashed line.

Membrane bioreactor

The MBR process is a relatively new modification of the activated sludge process which may provide higher quality effluent, appropriate for DPR. Costs vary greatly with local construction and power rates, and cost functions are few. DeCarolis et al. (2007) estimated total capital and annual costs for 3,785.4 m³/d (1 million gallons per day (MGD)) MBR facilities of $0.533–$0.682/m³ water treated, in which total capital cost ranges from $1,419,000 to $2,330,000, and the corresponding annual O & M cost is $218,000–$302,000. Membrane replacement (28%) and energy costs (34%) were found to be the largest components of O & M expense, and continues with equipment repair/replacement (19%). Another report by DeCarolis et al. (2004) showed that the total capital and operating cost for 3,785.4 m³/d (1 MGD) MBR raw wastewater reclamation systems ranged from $0.478 to $0.592/m³, supporting their subsequent conclusion that the total cost of MBR facilities is relatively constant (DeCarolis et al. 2007). For a 1.89 m³/d (500 GPD) onsite MBR system, a capital cost of $54,000 and annual O & M cost of $600 are indicated based on prices obtained in current research, development, and construction of a DPR system (Englehardt et al. 2013). These data are shown in Figure 2, along with Equation (1) fitted to the same data ($R^2 = 0.996$ and 0.999 for capital and operating costs, respectively). The capital costs in Figure 2 include MBR, mechanical components, pump, chlorine dosing system, land, and engineering fee. Annual O & M costs include electrical power, equipment repairs, chemical cleaning, membrane replacement, and other labor. Economy of scale is seen for both capital and O & M costs.

Coagulation and flocculation

Coagulation and flocculation can effect colloid-scale removal at larger nominal filtration pore sizes, and aid in
removal of phosphorus, metals, organics, and other constituents. Estimated costs of coagulation at neutral pH, assuming 56.5 mg/L of coagulant dose (alum or ferric) and 2.5 mg/L of caustic dose, can be estimated using an online simulation tool developed by the Water Research Foundation (2009) and US EPA (2007), as shown in Figure 3 for plant capacities 37.85, 378.5, 3,785, 37,850, 378,500 m³/d. Capital costs include upgrades to existing chemical feed systems, piping and valves, and instrumentation and controls. O & M costs include chemicals, power, replacement parts, and maintenance labor. Also, data obtained in current research and development (Englehardt et al. 2013) suggest a capital cost of $1,500 and annual O & M cost of $600 in 2012 for a 1.51 m³/d (400 GPD) coagulation system. Those data and the fitted Equation (1) are shown in Figure 3 (R² = 0.990 and 0.999 for capital and O & M costs, respectively). Economy of scale is found for both capital and O & M costs.

Electrocoagulation represents an economical coagulation approach avoiding the introduction of soluble anions, e.g. sulfate or chloride. Bayramoglu et al. (2004) presented a simplified operating cost analysis for the treatment of a textile wastewater by electrocoagulation using iron and aluminum electrodes. While no identical/different cost function related to scale is reported, they suggested an operating cost function of the form $C = a \cdot C_{\text{energy}} + b \cdot C_{\text{electrode}}$, in which a is electrical energy price, b is electrode material price, $C_{\text{energy}}$ and $C_{\text{electrode}}$ are consumption quantities per kilogram of chemical oxygen demand (COD) removed. Assuming an industrial electrical energy price, $a = 0.06$/kWh, and electrode material price at $1.80$/kg for aluminum and $0.30$/kg for iron, they found an operating cost of $0.3–0.6$/kg COD for aluminum electrodes and $0.1–0.2$/kg COD for iron. The latter represents ~$14,000/year for a 5,000 m³/d plant removing 50 mg/L COD. The authors also noted that lower initial pH and higher conductivity result in lower energy consumption.

**Reverse osmosis**

RO is employed in many reuse systems. Pretreatment comprising for example coagulation/flocculation, sedimentation, filtration, and/or disinfection is required in order to meet potable water standards (Bixio et al. 2005). Côté & Liu (2004) discussed two options for pretreatment in reuse applications: conventional activated sludge treatment followed by tertiary filtration, and integrated MBR treatment. Côté et al. (2005) estimated the capital cost at $161/(m³·d) for infrastructure and pretreatment, and $321/(m³·d) for the RO process, assuming membrane pretreatment, 75% recovery, 20 L/(m²·h) of flux, and 15.6 bar of pressure, not considering concentrate disposal costs. Total life-cycle costs were estimated at $0.07/m³ capital cost plus $0.21/m³ O & M, for a total $0.28/m³ to produce potable water from secondary effluent.

Although Akgul et al. (2008) reported a similar cost for RO seawater desalination in Turkey, water desalination applications in general have been suggested to be doubly-expensive relative to water reuse and reclamation (Côté et al. 2005). Assuming only 30–40% recovery, a 3–5 year membrane life, 15 year system design life, and $0.06$/kWh of energy, unit capital cost is found as approximately $0.375/m³ at a capacity of 250 m³/d, decreasing slowly up to 2,000 m³/d capacity at which point cost becomes constant at approximately $0.175/m³, while the unit operating cost is reported almost stable at ~$0.20/m³.

At the onsite system scale, data collected in current research and development (Englehardt et al. 2013) indicate a capital cost of $5,750 in 2012 and an annual O & M cost of $1,000 for a 2,200 GPD (8.33 m³/d) RO system without pretreatment. The online simulation tool from Water Research Foundation (2009) and US EPA (2007) also provides cost analysis of RO systems. Cost functions shown in Figure 4 were found by fitting all available data. Capital cost in Figure 4 includes membrane and infrastructure, including feed pumps, associated chemical feed equipment, and electrical and instrumentation, but not pretreatment, which is specific to source water quality. O & M costs are based on data reflecting 40% recovery and 14.2 L/(m²·h) for 250 and 2,000 m³/d capacities (Akgul et al. 2008), 75% recovery and 20.0 L/(m²·h) for 75,000 m³/d (Côté et al. 2003).
and data for capacities of 37.85, 378.5, 3,785, 37,850, 378,500 m³/d from Water Research Foundation (2009) and US EPA (2007). O&M costs include power, replacement parts, membrane replacement, and maintenance labor. Also, cost data from Akgul et al. (2008) have been divided by a factor of 2.2, the reported ratio of the cost for desalination versus water reclamation applications (Côté et al. 2005). Non-linear regression $R^2$ values of 0.978 and 0.954 were found for capital and operating cost. However, in general, O&M cost can vary significantly due to variations in recovery rate, RO flux, membrane life, and pretreatment. Slight economy of scale is evident in both capital and O&M costs. In general, RO costs appeared to be most variable among the water reuse technologies reviewed, and the cost function presented here is intended only for preliminary analysis.

**Ultrafiltration**

Ultrafiltration is a relatively low-energy, high efficiency filtration process, successfully employed in water reuse applications. Pickering & Wiesner (1995) presented a model of low-pressure membrane filtration cost which indicates that ultrafiltration and other membrane filtration processes are typically less expensive than conventional filtration for plant capacity less than 48,000 m³/d. Also, a study of Drouiche et al. (2001) indicated that a 480 m³/d drinking water system employing ultrafiltration of surface water in the Kabylia region of Algeria incurred a total capital and operational cost of $0.234/m³. Amortized capital cost over the 15 year period was considered the largest expense, at $0.117/m³, followed by interest on the invested capital at $0.052/m³ (3% annually), maintenance at $0.026/m³ (assumed as 1.5% per year), and membrane replacement at $0.025/m³. Costs for other items including power, cleaning, and labor were relatively small. In addition, the online simulation tool developed by the Water Research Foundation (2009) and US EPA (2007) gives estimated costs for ultrafiltration and microfiltration as shown in Figure 5 for 37.85, 378.5, 3,785, 37,850, 378,500 m³/d plant capacities. Costs obtained in current research and development (Englehardt et al. 2013) indicate a capital cost of $10,000 and annual O&M cost of $300 in 2012 for a 1.51 m³/d (400 GPD) ultrafiltration system. Non-linear regression fitting of the simulation tool and onsite data to Equation (1) is shown in Figure 5 ($R^2 = 0.988$ and 0.990 for capital and operating costs, respectively). Capital costs do not include pretreatment and post-treatment. O&M costs include power, replacement parts, membrane replacement, chemicals, and maintenance-related labor. Economy of scale is evident for capital cost, but not O&M.

**Peroxone (hydrogen peroxide/ozone) for organics mineralization**

Ozone is useful for disinfection without the introduction of chlorides, and the emerging hydrogen peroxide–ozone, or peroxone, process (Crittenden et al. 2012) is efficient for the advanced oxidation of organic constituents in secondary effluent (Englehardt et al. 2013). In this study it was desired to preliminarily assess the cost of the peroxone process if...
used in the future for complete COD mineralization, to address potential issues with disinfection byproducts and endocrine disrupting constituents in recycled water. Information on process costs as a function of plant capacity is currently limited. However, The Metropolitan Water District of Southern California (MWDSC) & James M. Montgomery Consulting Engineers Inc. (1991) estimated that, for a new 378,500 m$^3$/d (100 MGD) peroxone treatment plant, designed to disinfect and remove the taste/odor compounds geosmin and methylisoborneol at 2 mg/L ozone dose, peroxone system costs can be estimated at $9.0 million capital and $0.55 million annual O & M. Cost estimates in 1997 US dollars are also given for five scenario plants assuming an air-fed ozone generator capable of supplying a maximum ozone dose of 2.0 mg/L and an average dose of 1.5 mg/L, an air preparation system, buildings, a 25% uncertainty factor, 20% for engineering and administration, and another 25% for contingency. Because current research indicates that a dose of 130 mg/L may be required for effective mineralization of total COD (Wu et al., 2013; Englehardt et al., 2013), assumed plant capacities for the MWDSC data were reduced by a factor of 65. In addition, current research and development (Englehardt et al., 2013) suggests a capital cost of $35,000 and annual O & M cost of $500 for a 1.51 m$^3$/d (400 GPD) peroxone system, a capital cost of $45,000 and annual O & M cost of $1,000 for a 3.03 m$^3$/d (800 GPD) system, and a capital cost of $55,000 and annual O & M cost of $2,000 for a 5.68 m$^3$/d (1,500 GPD) system, all in 2012 US dollars. The cost functions developed by regression from all of these data are shown in Figure 6 (Equation (1), $R^2 = 0.999$ and 0.999), though these preliminary curves should be used with caution. In general, economy of scale is indicated for capital cost. Costs for disinfection alone can be estimated by multiplying assumed plant capacity by 65. It should also be noted that costs for such systems may fall significantly with further development and increased population.

**Granular activated carbon**

GAC may represent a relatively low-energy process, when used for polishing and redundancy in water reuse systems so that required reactivation/recharge is minimal. Cost functions for concrete gravity contactors and pressure contactors for field-scale systems, and general capital cost function for various GAC systems, were presented by Clark (1987) and Clark & Lykins (1989). The multiple cost functions identified are in similar form to Williams Law, and can be used to generate detailed cost estimates for different aspects of particular GAC systems based on capacity parameters such as total GAC volume/mass, system flow rate, and contactor cross-sectional area.

For general cost estimation, Water Research Foundation (2009) and US EPA (2007) developed an online simulation tool which gives total cost as a function of system capacity, as shown in Figure 7 for plant capacities 37.85, 378.5, 3,785, 37,850, 378,500 m$^3$/d. For onsite systems, current research and development (Englehardt et al., 2013) suggests a capital cost of $3,500 and an annual O & M cost of $1,000 in 2012 US dollars, for a 1.51 m$^3$/d (400 GPD) GAC system. Capital costs include the addition of GAC contactors, initial carbon charge, associated piping and valves,
and instrumentation and controls. O&M costs include spent GAC reactivation, power, replacement parts, and maintenance labor. Due to the recency and completeness of these data sources taken together, a general cost function was fitted to the output of the online simulation tool and the onsite data, as shown in Figure 7 \( R^2 = 0.996 \) and 0.991.

### Cost function summary

The cost functions for the technologies reviewed in this section are not universal. Local construction requirements vary widely, and combined systems may have different cost functions when applied in water and wastewater treatment regarding different influent quality and requirement of treated water. COWI Consulting (2005) suggests that for conventional treatment of surface water including pretreatment, coagulation/flocculation, sedimentation, filtration and disinfection, a capital cost function would be \( C = 18,200 \cdot Q^{0.51} \), in which \( C \) is the capital cost (€), and \( Q \) is the flowrate (m\(^3\)/d). O & M cost can be assumed at 8% of the capital cost. For a small 50–750 m\(^3\)/d domestic wastewater treatment plant using an optimized combined sand filtration and ozone process, total capital and operational cost for 5 years was reportedly about €0.1–0.32/m\(^3\) (Ni et al. 2003). Overall, the cost functions reported here represent a basis for screening and scaling of water reuse treatment processes. A summary of cost functions for these water reuse unit processes is given in Table 1.

### EXPERIENCE WITH WATER REUSE ECONOMICS VERSUS SYSTEM SCALE

Potable reuse systems have been implemented several times at differing scales in differing contexts. A review of the economics versus the scale of previous known implementations of potable reuse is given in this section.

#### Table 1 | Summary of cost functions of water reuse technologies (y is cost (€), x is capacity (m\(^3\)/d))

<table>
<thead>
<tr>
<th>Water reuse technologies</th>
<th>Capital cost</th>
<th>Annual O &amp; M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activated sludge</td>
<td>( \log (y) = 0.256 \cdot (\log (x))^{1.556} + 4.545 )</td>
<td>–</td>
</tr>
<tr>
<td>Membrane bioreactor</td>
<td>( \log (y) = 0.569 \cdot (\log (x))^{1.155} + 4.605 )</td>
<td>( \log (y) = 0.639 \cdot (\log (x))^{1.145} + 2.633 )</td>
</tr>
<tr>
<td>Coagulation and flocculation</td>
<td>( \log (y) = 0.222 \cdot (\log (x))^{1.516} + 3.071 )</td>
<td>( \log (y) = 0.347 \cdot (\log (x))^{1.448} + 2.726 )</td>
</tr>
<tr>
<td>Reverse osmosis</td>
<td>( \log (y) = 0.966 \cdot (\log (x))^{0.929} + 5.082 )</td>
<td>( \log (y) = 0.534 \cdot (\log (x))^{1.255} + 2.786 )</td>
</tr>
<tr>
<td>Ultrafiltration</td>
<td>( \log (y) = 1.003 \cdot (\log (x))^{0.830} + 3.832 )</td>
<td>( \log (y) = 1.828 \cdot (\log (x))^{0.598} + 1.876 )</td>
</tr>
<tr>
<td>Peroxone (mineralization)</td>
<td>( \log (y) = 0.405 \cdot (\log (x))^{1.428} + 4.528 )</td>
<td>( \log (y) = 0.845 \cdot (\log (x))^{1.057} + 2.606 )</td>
</tr>
<tr>
<td>Granular activated carbon</td>
<td>( \log (y) = 0.722 \cdot (\log (x))^{1.023} + 5.443 )</td>
<td>( \log (y) = 1.669 \cdot (\log (x))^{0.559} + 2.371 )</td>
</tr>
</tbody>
</table>

#### Biosphere 2

In the Biosphere 2 closure experiment, eight researchers lived under a transparent 12,700 m\(^2\) (3.14 acre) dome containing an artificial ecosystem from 1991 to 1993. An external energy system provided partial water supply to the crew inside (Dempster 1999). Both heating and cooling were provided by hot, cooled, and chilled water circulated from a closed piping system outside, through a heat exchanger in Biosphere 2. In the heat exchanger, 25 air handlers forced air circulation, each capable of an airflow up to 24 m\(^3\)/s. Thus while maintaining the temperature and humidity, the system also condensed 20–40 m\(^3\)/d from the vapor in the atmosphere for potable uses. Water collected was used for drinking directly after UV sterilization. A separate water treatment system handled toilet, kitchen, and lab wastewater. Treatment consisted of anaerobic holding tanks and application to an agricultural system providing an environmental buffer (Nelson et al. 1999). An 870 m\(^3\) storage tank equalized flow. Electrical power required by fans, pumps, and communications averaged about 700 kW, or more than $50,000/month, provided by the external energy house. The annual cost of fuel in the compressive chiller and hot water boiler was approximately $1 million (Dempster 1999). Thus the extreme energy demand of this system resulted in costs that would be prohibitive in most applications.

#### Windhoek, Namibia

The city of Windhoek, Namibia, population 240,000, built the Goreangab Water Reclamation Plant, a DPR facility, in the 1960s due to local water supply shortage and variability (Lahnsteiner & Lempert 2007). With an initial capacity of 3,287 m\(^3\)/d, and ultimately 7,500 m\(^3\)/d, the plant produced 12–18% of the total potable water supply for over 30 years. In 2002, a €12.5 million New Goreangab Water
Reclamation Plant was built. Project influent was unchlorinated secondary effluent. The progressive city water price of $0.72/m³ for 0–0.2 m³/d; $1.18/m³ for 0.201–1.8 m³/d; and $2.22/m³ for >1.8 m³/d in 2004 was reasonable in comparison with US prices of ca $0.40/m³. Based on Canizares et al. (2009), the capital cost of ozonation cost can be estimated as $ = 2,359.85 + (V/12)0.6143 after conversion to 2012 US dollars, where V is the flow rate (m³/d) and P is the capital cost ($) assuming ozone dosage at 2 mg/L. Given a similar treatment train comprising enhanced coagulation and flocculation, ozonation, GAC filtration, and ultrafiltration, without chlorine disinfection or stabilization, and assuming the 21,000 m³/d capacity of the new plant, a capital cost of $21.3 million (2012 US dollars) would be estimated using the equations in Table 1.

Denver potable water project

From 1979 to 1992, the Denver Potable Water Reuse Demonstration Project demonstrated the conversion of unchlorinated secondary effluent into water that could be directly piped into a drinking water distribution system. Product water from the 3,785.4 m³/d (1.0 MGD) plant was not used for drinking, but stored and shown as part of the project’s public program (Rogers & Lauer 1992). The plant’s construction cost was $18.5 million, with $6.0 million for scientific studies on health risks, and $8.4 million O&M over the 13 years (Lauer 1993). For a similar system comprising flocculation, reverse osmoses, two stages of GAC, ozonation, and ultrafiltration, without lime treatment, recarbonation, air stripping, UV or chloride dioxide disinfection, at a capacity of 3,785.4 m³/d, a capital cost of $9.7 million would be estimated using the equations of Table 1.

International Space System

As of November 2008, the International Space System developed by NASA included a Water Recovery System consisting of Water Processor Assembly and Urine Processor Assembly (Carter 2009). The system provided drinking water to a crew of six members, and was derived from a combination of condensate and urine. Flush water and urine were treated with a formula containing chromium trioxide and sulfuric acid. From there the water passed to a distillation assembly, consisting of a rotating centrifuge where the wastewater and urine stream were evaporated and condensed. The Urine Processor Assembly was designed for a load of 9 kg/d (19.8 lb/d) and could recover a minimum of 85% of the water content, essentially equivalent to the six-crew requirement. The Water Recovery System reportedly averaged 743 W power consumption while in operation, and 297 W while in standby, or less than perhaps $40/month, high for six people.

Village of Cloudcroft

Due to lack of sufficient water supply from local springs and wells, the village of Cloudcroft, New Mexico, USA, population 850 increasing to more than 2,000 during holidays, constructed a system to provide potable water from purified wastewater (Livingston 2008). Following treatment by MBR, disinfection, RO, and UV/hydrogen peroxide advanced oxidation, the treated municipal wastewater is blended with approximately 50% spring or well water. The blended water is detained for 2 weeks in a storage reservoir, after which it undergoes ultrafiltration, UV disinfection, and activated carbon adsorption. With a treatment capacity of 378.5 m³/d (100,000 GPD), capital cost of the project is roughly $3,500,000, with operating costs of $50,000/year and equipment maintenance costs of $0.21/m³. Overall, the cost of operation and maintenance is $0.63/m³, and the total cost of product water is $2.38/m³. Given a similar system comprising MBR, RO, peroxone, ultrafiltration, and GAC at a capacity of 378.5 m³/d, a capital cost of $3.5 million (without UV disinfection) would be estimated using the equations of Table 1.

Chanute, KS

During a severe drought, the city of Chanute, Kansas, USA, population 12,000 at the time, implemented emergency wastewater reclamation and reuse for municipal water supply from October 1956 to March 1957 (Mangan 1978; Asano et al. 2007). The Neosho River, previously used to supply the city water demand of 5,300 m³/d (1.4 MGD), was dammed upstream of the treatment plant, and sewage treatment plant effluent was returned to the river as source water. Treatment comprised standard 1950s physical–chemical technology, including alum flocculation, sedimentation, sand filtration and chlorine disinfection. Activated carbon and membrane filtration were not available. Assuming a similar treatment train consisting of activated sludge and flocculation, without sand filtration and chlorine disinfection in Metzler et al. (1958), at a capacity of 5,300 m³/d, a capital cost of $3.4 million would be estimated using the equations of Table 1.

Big Spring, TX

Due to a long-term drought in the Permian Basin of West Texas, the Colorado River Municipal Water District, which
supplies water to the cities of Odessa, Big Spring and Snyder, recently launched a wastewater reuse project. The plan is to treat 7,949.4 m$^3$/d (2.1 MGD) of filtered secondary effluent with membrane filtration, RO, and UV/hydrogen peroxide oxidation; blend it with raw water in the transmission line; and pass the water to a potable water treatment process which includes flocculation, sedimentation, granular media filtration and disinfection, before release to the distribution network to comprise ca 5% of the finished water. In the preliminary design report (Sloan 2007), construction cost was estimated to be $8.23 million, including $3.45 million for treatment equipment, $0.88 million for the pump station, and $0.70 million for the pump line. Annual operating cost was estimated at $667,000 for power, chemical, labor and equipment replacement. Produced water is projected to be $0.68/m$^3$. Total energy consumption for operation of the membrane treatment, UV oxidation, and source water and product water pumping is projected at 1.41 kWh/m$^3$. This is comparable to the current local operating cost of 1.33 kWh/m$^3$, due principally to the long pumping distance and the 914.4 m (3,000 ft) elevation of Big Spring (Sloan et al. 2000). Assuming membrane filtration, RO, UV/hydrogen peroxide oxidation, coagulation, and granular media filtration at a capacity of 7,949 m$^3$/d, a capital cost of $14.6 million (without disinfection) can be estimated using the equations of Table 1.

**Orange County Water District, CA**

The Orange County Water District’s Groundwater Replenishment System treats disinfected secondary effluent with microfiltration, RO, and UV/hydrogen peroxide oxidation, and product water is used to recharge existing groundwater basins. The augmented Orange County groundwater basin supplies water for roughly 2.5 million people, while receiving up to 265,000 m$^3$/d of treated wastewater for recharge (Markus et al. 2008; Deshmukh 2003; Tchobanoglous et al. 2011). This $481 million project had an annual budget of ~$34 million (Woodside & Westropp 2009). Assuming an engineering process comprising microfiltration, three stages of RO, and UV/hydrogen peroxide oxidation at a capacity of 265,000 m$^3$/d, a capital cost of $253.8 million can be estimated using the equations of Table 1.

**Pure Cycle Corporation**

In the 1970s, the Pure Cycle Corporation developed a complete closed-loop DPR system for single homes. These units were installed primarily in mountain homes in Colorado from 1976 to 1982 (M. Harding, Pure Cycle Corp., personal communication). The system consisted of a wastewater holding tank, a biological digester, an ultrafiltration unit, and a deionization unit (Sellby & Pure Cycle Corp. 1979). A central control system communicated with company headquarters in Denver. After the company exited the business due to the expense of maintaining single systems scattered throughout the mountains, homeowners obtained permission from the State to operate the systems independently. While operating costs are not available for these systems, one could assume a cost of <$1.32/m$^3$ water treated for acid and base regenerant, assuming on the order of 100 mg/L ions removed, to be a dominant operating cost. The cost of brine evaporation or disposal is not known.

**Singapore NEWater Project**

With a large urban population and limited land area, the Singapore city-state launched the NEWaterProject in 2002, to reuse clarified secondary effluent as a supplemental water supply (Singapore Water Reclamation Study 2002). Treatment comprises microfiltration, RO, and UV disinfection, followed by blending with reservoir water for potable use. Recycled water contributed only ~2% to the finished potable water as of 2010. Two 72,000 m$^3$/d plants were commissioned in January 2003. A third 24,000 m$^3$/d plant began supplying water in January 2004, and a fourth 148,000 m$^3$/d plant was brought online January 2005 (Asano et al. 2007). Cost of the product water including production, transmission and distribution was about S$1.30/m$^3$ in 2003, decreasing to S$1.00/m$^3$ (US $0.66/m^3$) by April 2007 (Zhang et al. 2009). Assuming microfiltration, and RO at a capacity of 316,000 m$^3$/d, a capital cost of $152.8 million (without disinfection) can be estimated using the equations of Table 1.

**Case study summary**

A summary of the scales and costs of previous potable reuse implementations is given in Table 2, based on the information in this section. Capital costs estimated as described for each case study in this section, using the cost functions developed in this work, are also shown in the table. Despite the site-specificity of many labor, construction, and other costs, predicted costs are generally within a factor of two relative to reported costs, except for the Denver research and demonstration project, which may have phases not reflected in estimated costs. Also, no obvious bias is apparent.
### Table 2 | Summary of reported and projected reuse case study costs in constant 2012 US dollars proportional to the GDP deflator (US Bureau of Economic Analysis 2013)

<table>
<thead>
<tr>
<th>Case name</th>
<th>Total scale</th>
<th>Capital cost</th>
<th>Capital cost per average home served*</th>
<th>Annual operation cost</th>
<th>Unit operating cost of water</th>
<th>Water reuse technologies</th>
<th>Estimated capital cost with cost functions available in Table 1 Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biosphere 2</td>
<td>20–40 m³/d</td>
<td>–</td>
<td>–</td>
<td>$2.13 million</td>
<td>$145.89–291.78/m³</td>
<td>Condensation</td>
<td>–</td>
</tr>
<tr>
<td>Windhoek</td>
<td>21,000 m³/d</td>
<td>$17.0 million (€12.5 million in 2007)</td>
<td>$920</td>
<td>–</td>
<td>$0.40/m³ (€0.30/m³ in 2007)</td>
<td>Enhanced coagulation and flocculation, ozonation, GAC filtration, ultrafiltration, disinfection and stabilization</td>
<td>$21.3 millione</td>
</tr>
<tr>
<td>Denver Potable Water Project</td>
<td>3,785.4 m³/d (1 MGD)</td>
<td>$27.8 million</td>
<td>$8,325</td>
<td>$975,000</td>
<td>$0.68/m³</td>
<td>Filtration, UV irradiation, reverse osmoses, air stripping, ozonation, chloramination, and ultrafiltration</td>
<td>$9.7 millione</td>
</tr>
<tr>
<td>International Space System</td>
<td>0.0078 m³/d</td>
<td>–</td>
<td>–</td>
<td>$504</td>
<td>$177.03/m³</td>
<td>Condensate and urine vacuum distillation</td>
<td>–</td>
</tr>
<tr>
<td>Village of Cloudcroft</td>
<td>378.5 m³/d (0.1 MGD)</td>
<td>$3.71 million</td>
<td>$11,130</td>
<td>$53,000</td>
<td>$0.67/m³ ($2.40/1,000 gallons)</td>
<td>Membrane bioreactor, disinfection, RO, and UV/hydrogen peroxide advanced oxidation</td>
<td>$3.5 million</td>
</tr>
<tr>
<td>Chanute, KS</td>
<td>5,300 m³/d (1.4 MGD)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>&lt;$1.05/m³ ($4/1,000 gallons)</td>
<td>Activated sludge, alum coagulation and flocculation, sedimentation, sand filtration, and chlorine disinfection</td>
<td>$3.4 million</td>
</tr>
<tr>
<td>Big Spring, TX</td>
<td>7,949.4 m³/d (2.1 MGD)</td>
<td>$8.89 million</td>
<td>$1,067</td>
<td>$720,000</td>
<td>$0.73/m³ ($2.59/1,000 gallons in 2007)</td>
<td>Membrane filtration, RO, and UV/hydrogen peroxide oxidation, flocculation, sedimentation, granular media filtration and disinfection</td>
<td>$14.6 millione</td>
</tr>
<tr>
<td>Orange County Water District, CA</td>
<td>265,000 m³/d (70 MGD)</td>
<td>$505 million</td>
<td>$2,164</td>
<td>$35.7 million</td>
<td>$1.26/m³ ($4.55/1,000 gallons in 2009)</td>
<td>Microfiltration, 3 stages of RO, and UV/hydrogen peroxide oxidation</td>
<td>$253.8 millione</td>
</tr>
<tr>
<td>Pure Cycle Corporation</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>&lt;$1.32/m³</td>
<td>Biological digestion, ultrafiltration, and deionization</td>
<td>–</td>
</tr>
<tr>
<td>Singapore NEWater Project</td>
<td>516,000 m³/d</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>$0.69/m³</td>
<td>Microfiltration, RO and UV disinfection</td>
<td>$152.8 millione</td>
</tr>
</tbody>
</table>

*Assumes water usage of 1.14 m³/d (300 GPD) per home.

1Calculated based on 81% reported Urine Processor Assembly recovery of 180 kg urine in 6 weeks, and the ratio of the flow rate of Urine Processor Assembly to Water Processor Assembly (Carter 2009).

1The city denied the decision of transport water at $4/1,000 gallons for cost and physical limitation (Metzler et al. 1958).

1Based on estimated cost of acid and base regenerant, for removal of on the order of 100 mg/L ions.

1Primary and secondary treatment not included.

1Calculation based on actual flow rate rather than design flow.
CONCLUSIONS

The applicability of distributed DPR systems will likely depend in part on local topographic, demographic, and hydrologic characteristics, on needs for reductions in energy consumption for water conveyance, and on projected increases in water demand. When substantial investment has previously been made in centralized water/wastewater treatment systems, the scaling of potable water reuse systems may be largely determined by existing infrastructure. However, much of the water/wastewater infrastructure in the USA today is in need of repair and/or replacement, and therefore information on the cost of current technologies versus system scale will be needed. In particular, the following conclusions were drawn based on the literature reviewed.

1. A logarithmic variant of the Williams Law cost function appears to apply satisfactorily to both capital and O&M cost of water reuse technologies, over orders of magnitude in system capacity.
2. The cost functions found in the literature and derived in this work were roughly demonstrated versus available data on DPR systems.
3. Results indicate that economies of scale apply for many unit processes. However, capital and operating costs for collection/distribution networks counterbalance these economies in centralized systems. Therefore, study of the optimal scale of distributed DPR systems is recommended, along with further study of the costs of emerging processes.

ACKNOWLEDGEMENTS

The support of the US National Science Foundation (Award No. 1038527) for this work is gratefully acknowledged. Also, anonymous reviewers are thanked for their input and constructive suggestions regarding earlier versions of the paper.

REFERENCES


Sauer, P. & Kimber, A. 2002 Energy Consumption and Costs to Treat Water and Wastewater in Iowa. Iowa Association of Municipal Utilities, Ankeny, IA, USA.


