Resources, Conservation & Recycling 145 (2019) 94–112

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Wastewater-based resource recovery technologies across scale: A review

Nancy Diaz-Elsayed, Nader Rezaei, Tianjiao Guo[1], Shima Mohebbi[2], Qiong Zhang*

Department of Civil and Environmental Engineering, University of South Florida, 4202 E. Fowler Avenue, Tampa, FL, 33620, USA

ARTICLE INFO

Keywords:
Water reuse
Energy recovery
Nutrient recovery
Wastewater treatment
System scale

ABSTRACT

Over the past few decades, wastewater has been evolving from a waste to a valuable resource. Wastewater can not only dampen the effects of water shortages by means of water reclamation, but it also provides the medium for energy and nutrient recovery to further offset the extraction of precious resources. Since identifying viable resource recovery technologies can be challenging, this article offers a review of technologies for water, energy, and nutrient recovery from domestic and municipal wastewater through the lens of the scale of implementation. The system scales were classified as follows: small scale (design flows of 17 m^3/day or less), medium scale (8 to 20,000 m^3/day), and large scale (3800 m^3/day or more). The widespread implementation of non-potable reuse (NPR) projects across all scales highlighted the ease of implementation associated with lower water quality requirements and treatment schemes that resembled conventional wastewater treatment. Although energy recovery was mostly achieved in large-scale plants from biosolids management or hydraulic head loss, the highest potential for concentrated nutrient recovery occurred in small-scale systems using urine source separating technologies. Small-scale systems offered benefits such as the ability for onsite resource recovery and reuse that lowered distribution and transportation costs and energy consumption, while larger scales benefited from lower per unit costs and energy consumption for treatment. The removal of pharmaceuticals and personal care products remained a challenge across scales, but unit processes such as reverse osmosis, nanofiltration, activated carbon, and advanced oxidation processes exhibited high removal efficiency for select contaminants.

1. Introduction

Water is one of the most important resources for human life and production activities. While most of the current fresh water supply relies on surface rivers, lakes, and underground aquifers, its over-exploitation has raised concerns and is very likely stressed by climate change, increasing land use, economic growth and urbanization (Vörösmarty et al., 2000; Zimmerman et al., 2008; Gleeson et al., 2012). An expanding population would further increase the current water scarcity; based on the United States (US) Census Bureau's population projection for the next 50 years, a recent report by the US National Research Council (NRC, 2012) found that per capita water use in the US must decline further barring the development of major new resources. Compared to other water sources such as desalinated seawater, harvested rainwater, or water from melted icebergs, treated municipal wastewater provides a climate-independent high-quality fresh water source that can be locally controlled (Bloetscher et al., 2005) and has significant potential for helping to meet future water needs (NRC, 2012). In order to address the clean water challenge in a sustainable way, a paradigm shift must occur in wastewater management that emphasizes wastewater as a renewable resource, and a careful assessment of resource recovery systems is essential (Guest et al., 2009).

In the design of wastewater systems, scale has always been an important consideration. Historically, centralized wastewater treatment plants have played a significant role (Gikas & Tchobanoglous, 2009), in part, because of the improved quality control and economies of scale for treatment. However, in many cases, due to topography, population density, and/or population distribution, centralized systems can be infeasible or too costly (Libralato et al., 2012), and the implementation of small- to medium-scale wastewater treatment facilities began receiving more attention (Gikas & Tchobanoglous, 2009). In fact, studies have shown that small-scale distributed treatment systems can be economically feasible if the costs of the distribution network are included (Maurer et al., 2006; Eggiman et al., 2015; Guo & Englehardt, 2015). As for decentralized systems where wastewater is treated and

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* Corresponding author at: 4202 E. Fowler Avenue, ENG 030, University of South Florida, Tampa, FL, 33620-5350, USA.
E-mail address: qiongzhang@usf.edu (Q. Zhang).

[1] Present affiliation & address: Institute of Industrial Ecology and Environment, Zhejiang University (Yuquan Campus). No. 38 Zheda Rd., Hangzhou, Zhejiang, 310027, China.

[2] Present affiliation & address: School of Industrial and Systems Engineering, University of Oklahoma, 202 W. Boyd St., Norman, Oklahoma, 73019 USA.

https://doi.org/10.1016/j.resconrec.2018.12.035
Received 1 October 2018; Received in revised form 12 December 2018; Accepted 29 December 2018

Nomenclature

gpcd	gallons per capita per day
ABW	automatic backwash
AWPF	Advanced Water Purification Facility
BAC	biological activated carbon
BAF	biologically aerated filtration
BOD	biochemical oxygen demand
BOD5	5-day biochemical oxygen demand
CAS	conventional activated sludge
CBOD5	5-day carbonaceous biochemical oxygen demand
CFR	Code of Federal Regulations
CHP	combined heat and power
CMF	cloth media filter
DF	drainfield
DPR	direct potable reuse
EPA	Environmental Protection Agency
GAC	granular activated carbon
GAP	Green Acres Project
GP	grind pumper
GPD	gallons per day
GW	greywater
GWR	groundwater recharge
GWRS	Groundwater Replenishment System
HWW	household wastewater
IPR	indirect potable reuse
IX	ion exchange
K	potassium
MBC	Metro Biosolids Center
MBR	membrane bioreactor
MF	microfiltration
MGD	million gallons per day
MMF	multi-media filtration
N	nitrogen
ND	not detectable
NGWRP	New Goreangab Water Reclamation Plant
NPR	non-potable reuse
NS	not specified
NSF	National Sanitation Foundation
O&M	operation and maintenance
OGWRP	Old Goreangab Water Reclamation Plant
OCSD	Orange County Sanitation District
P	phosphorus
PB	purification bed
PE	person-equivalents
PF	peaking factor
RBC	rotating biological contactor
RC	recirculation
RO	reverse osmosis
RWW	raw wastewater
SB	sedimentation bed
SF	sand filtration
ST	septic tank
SWA	surface water augmentation
TN	total nitrogen
TP	total phosphorus
TSS	total suspended solids
UF	ultrafiltration
US	United States
USBF®	upflow sludge blanket filtration
USS	urine source separation
UV	ultraviolet
WASSTRIP®	Waste Activated Sludge Stripping to Remove Internal Phosphorus
WRF	water reclamation facility
WWTP	wastewater treatment plant

reused near the point of generation, they may have lower water and energy consumption (Bakir, 2001; Means et al., 2006), less vulnerability to natural disasters and terrorism (Wilderer & Schreff, 2000), and better resource recovery support (Brown et al., 2010; Libralato et al., 2012; Maurer, 2013). Additionally, satellite wastewater systems are also available choices to reclaim water at local facilities and return the residuals to centralized treatment systems downstream for further treatment (Tchobanoglous & Leverenz, 2013). While prior literature has reviewed available wastewater treatment technologies for water reuse (Asano et al., 2007), source separation technologies (Larsen et al., 2009), the cost of treatment processes for water reuse (Guo et al., 2014), and large-scale resource recovery solutions (Mo and Zhang, 2013), a comprehensive review of wastewater-based resource recovery technologies across small- to large-scale systems has not been

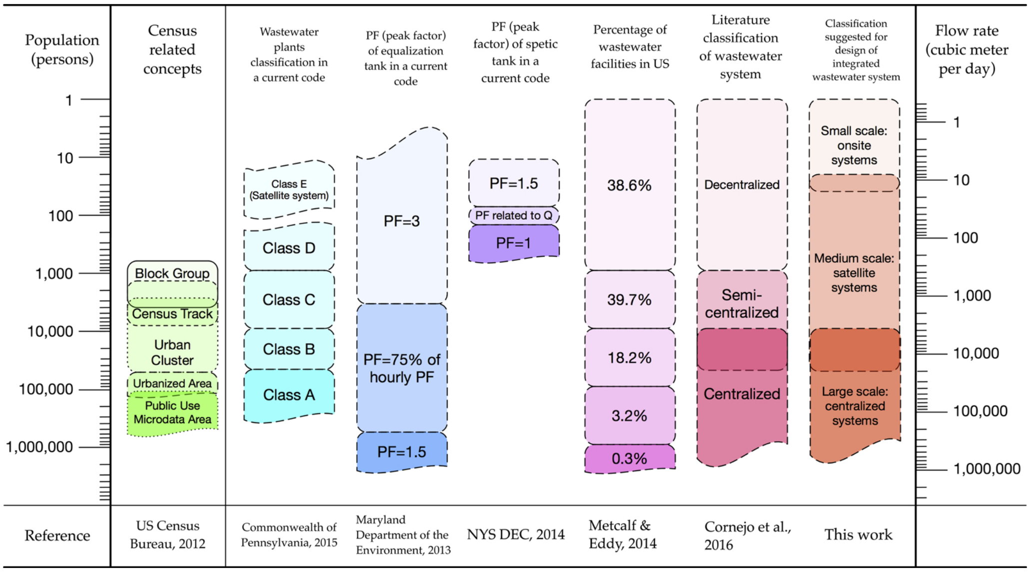

Fig. 1. Classification of wastewater systems in terms of size. Horizontal boundaries represent determined bounds, and curves as unspecified bounds.

conducted.

The objective of this study is to perform a literature review of peer-reviewed articles, book chapters, case studies, and government reports, and synthesize information to aid in the selection of technology for resource recovery and target resources to be recovered. This study is presented in the following structure: firstly, a classification of onsite, satellite, and centralized systems in terms of size is offered; mature technologies to recover water, energy, and/or nutrients from domestic and municipal wastewater are reviewed for each scale and benefits and challenges discussed; finally, the trends in technology selection and recovery performance are presented. Since a detailed description of the technologies is outside of the scope of this article, readers are encouraged to refer to other prominent resources mentioned throughout the manuscript as needed.

2. Classification based on system size

Considering the wide range of possible wastewater system sizes, systems should be classified in terms of flow rate or population served for the initial screening process in the design stage. In this section, current classifications related to city planning, water systems, and wastewater systems are reviewed, and a recommendation for classifying wastewater systems is presented.

The US Census Bureau and US Environmental Protection Agency (US EPA) developed categories based on population size. The smallest group listed in the US Census Bureau (2012) report was a Block Group consisting of 600 to 3000 people, and the largest was Public Use Microdata Areas of 100,000 people or more. While their clusters are not directly related to wastewater treatment, they provide basic information for consideration in classifying the capacity of an integrated wastewater system or selecting the size of the planning area.

Local codes are more popular for wastewater system classifications. For example, the state of Pennsylvania in the US classifies wastewater systems in terms of average daily flow (see Fig. 1) (Commonwealth of Pennsylvania, 2015). Many classifications use comprehensive point-based systems associated with treatment processes rather than only treatment capacity, or some combination thereof (Washington State Legislature, 2000; Maricopa County Environmental Services, 2007; Tennessee DEC, 2007; New Jersey DEP, 2008; Florida DEP, 2013; Newfoundland and Labrador DEC, 2014; British Columbia EOCPO, 2015; Idaho DEQ, 2015; Prince Edward Island DCLE, 2016). In the State of Idaho in the US, reaching a certain requirement in each unit process (preliminary, primary, secondary, or tertiary) grants specific points, and the whole system is then classified based on the accumulated points. In general, these classifications are for better administration for existing plants and assignation of operators.

Considering the flow fluctuation in small wastewater systems (Metcalf & Eddy, 2014), flow equalization may be especially needed for onsite and decentralized systems. Thus, classification of peak flow range in the sewer network may also be helpful in classifying integrated wastewater systems. In this vein, the Maryland Department of the Environment (2013) published a design guideline, which suggests a classification based on daily peaking factor (PF) (i.e., the ratio of the maximum daily flow to the average daily flow; hourly PF is the ratio of the maximum hourly flow to the average daily flow). For example, if a wastewater system has an average daily flow below 946 m^3/day (0.25 million gallons per day [MGD]), a PF of 3 is recommended and the design capacity will be 2839 m^3/day (0.75 MGD, PF multiplied by average daily flow). The New York State design guideline (NYS DEC, 2014) provides a similar classification for septic tanks that are of intermediate size (between onsite and large facilities), as displayed in Fig. 1.

Metcalf & Eddy (2014) used a log scale classification for a US wastewater treatment plant (WWTP) census by the US EPA (2008); data shows that ˜78% of WWTPs have flow rates less than 3785 m^3/day (1 MGD) even though they treat less than 8% of the total wastewater, which indicates a polarized distribution in current wastewater management. Additionally, Cornejo et al. (2016) discussed the impact of scale on the environmental sustainability of WWTPs with integrated resource recovery and classified systems as follows: decentralized systems at the household scale (< 379 m^3/day flow rate), semi-centralized systems at the community scale (379˜19,000 m^3/day) and centralized systems at the city scale (3,800˜57,000 m^3/day or larger).

Fig. 1 summarizes the current classification of systems. For estimation, the conversion of flow rate and population served for wastewater treatment facilities is based on the average US wastewater rate of 0.42 m^3/day per capita (110 gpcd, gallons per capita per day) (Metcalf & Eddy, 2014). To the best of our knowledge, no study has specified the size range of onsite, satellite, and centralized systems for design purposes. Thus, a classification that considers population coverage, treatment technology transition, and existing infrastructures and regulations is suggested (see Fig. 1):

1. *Small scale: onsite systems or decentralized systems (population: 1–40).* These systems likely employ a septic tank as the primary treatment technology for onsite treatment of wastewater (e.g., from a home, multi-unit complex, or commercial establishment). The upper bound comes from a conservative estimate of the number of people served with the largest commercial septic tank found (115 m^3) (Vaughn Concrete Products, Inc., 2015), and assumptions of maximum design flow of 0.95 m^3/day per capita (250 gpcd) and a hydraulic detention time of 3 days;
2. *Medium scale: satellite facilities or semi-centralized systems (population: 20–47,000).* The range of this type of system is determined from the definition of large-scale septic systems of 20 people or more (US EPA, 2012a) and the capacity of the largest satellite system in the US (20,000 m^3/day) (Tchobanoglous & Leverenz, 2013). These systems treat wastewater from buildings occupied by 20 or more people or from smaller communities with a population of less than 47,000 people. They may rely on membrane bioreactors or share similar treatment technologies as centralized ones, and their maximum capacity may cover the population of an Urban Cluster (< 50,000 persons); and
3. *Large scale: centralized systems (population* 9090 *or greater).* In the US, 93% of wastewater flow is treated by large systems, and currently many of the codes and guidelines are also directed towards them (Metcalf & Eddy, 2014). The lower bound comes from a plant with a 3785 m^3/day (1 MGD) capacity. For reference, one of the largest wastewater treatment facilities in the world, Chicago's Stickney Water Reclamation Plant, serves a population of 2.3 million people and has a capacity of 5.45 million m^3/day.

This classification is flexible given the overlap between the small- and medium-scale systems, as well as the medium- and large-scale systems and keeps the current understanding of onsite and centralized systems. In terms of system size, a combination of the three types of systems could cover the service area of any wastewater treatment system in the world today; satellite and centralized systems would nearly satisfy the range of current public water systems. The disadvantage of the classification is that it fails to consider detailed design parameters such as peak factor. Nonetheless, the ranges of the systems' classification will likely evolve as more research is done on integrated wastewater system design. The following sections reviewing resource recovery technologies will use this classification.

3. Small-scale systems

Small-scale systems serve 1–40 people and result in a flowrate of 17 m^3/day or less. The resources recovered at the small scale primarily consist of water and nutrients, but at least one option exists for energy recovery as well, which will be discussed in this section.

3.1. Overview

3.1.1. Energy recovery

Separating recoverable resources from greywater and blackwater, or nutrients from urine is a common practice for small-scale resource recovery projects. Thermal energy can be recovered when greywater is separated from the wastewater stream (see Fig. 2 for a summary of technologies). Although thermal energy recovery is not commonly implemented, areas with cold climates offer the most favorable conditions given the dependence on temperature differences between wastewater and its surroundings. Full-scale implementations vary from the household-level to large WWTPs. At the small scale, the NEXheater captures energy from household greywater and can reduce the energy used for water heating by 70% (Nexus, 2015, 2017). Another commercialized product, EcoDrain, offers thermal energy recovery via a heat exchanger applied to a shower drain with an expected payback period as low as 2.3 years (EcoDrain, 2019).

3.1.2. Nutrient recovery

Nutrients can be recovered via urine source separation, composting toilets, or fertigation (reclaimed water with nutrients) and reused locally to fertilize plants (Asano et al., 2007; Anand & Apul, 2014). Most of the nutrients in municipal wastewater are from urine, which contributes only ˜1% of total wastewater volume. In fact, approximately 80% of the nitrogen (N), 50% of the phosphorus (P), and 70% of the potassium (K) in municipal wastewater is from urine (Wilsenach et al., 2003). A person excretes about 4.37–4.55 kg N/year, 0.54-0.73 kg P/year, and 1.2–1.37 kg K/year via urine and feces (Anand & Apul, 2014).

For urine source separation, volume reduction can be achieved via evaporation, drying, or struvite precipitation to facilitate transportation. Pilot projects have been investigated or are underway around the world, including in Australia, Austria, China, Germany, the Netherlands, Sweden, Switzerland, and the United States (Schuetze and van Loosdrecht, 2010; Mitchell et al., 2013; Noe-Hayes et al., 2015). The average concentrations of the nutrients recovered in diluted and undiluted urine (from urine source separation systems) included 2900 and 6500 mg/L of total nitrogen, 200 and 300 mg/L of total phosphorus, and 1000 and 1400 mg/L of calcium, respectively (Mitchell et al., 2013). Agricultural trials were also conducted in the Australian study, which found that the phosphorus uptake was equally as efficient or higher from urine relative to phosphate fertilizer when applied to lettuce and pelargonium (Mitchell et al., 2013).

Composting toilets have been implemented in many building designs in the Living Building Challenge to reduce wastewater loads and recover nutrients (ILFI, 2017). The compost at the Bullitt Center (Seattle, Washington), for example, is a usable fertilizer, but must be treated by a biosolids processing center to meet regulatory requirements. In contrast, the Morris and Gwendolyn Cafritz Foundation Environmental Center (Accokeek, Maryland) uses the compost and leachate as a fertilizer for its landscape.

Nitrogen and phosphorus can be recovered across all scales via fertigation. The nutrients and reclaimed water offset the need for commercial fertilizers and potable water, respectively. The target water quality should account for soil characteristics, climate, plant type, and the irrigation method implemented (Asano et al., 2007). Water quality guidelines from the US EPA (2012b) for agricultural reuse and health-based targets developed by the World Health Organization are provided in Section 1.1 of the Appendix.

3.1.3. Water reuse

Across all scales, non-potable reuse (NPR) is the most prevalent application for water reuse. At the small scale, reuse applications primarily consist of irrigation and toilet flushing. In the US, the National Sanitation Foundation (NSF) developed the NSF 350 standard for onsite treatment for NPR, and NSF 350-1 for greywater treatment technologies for subsurface irrigation (NSF, 2019). The NSF 350 standard has been incorporated into multiple plumbing codes (IAPMO, 2015; ICC, 2015), including that of California (California Building Standards Commission, 2017). Certified NSF technologies include treatment via sand filtration and membrane bioreactors, and water quality parameters are summarized in Table 1 (NSF, 2017). The US EPA (2012b) recommends secondary treatment and disinfection for several NPR applications; filtration should be added when direct human contact is expected or to irrigate food crops that can be consumed raw.

The Nexus treatment unit treats greywater and consists of a “3 stage hybrid process that combines floatation, filtration and disinfection” (Nexus, 2015). The systems were installed in San Diego, California homes for \$10,000 each (the homes ranged in price from \$890k to \$1 M), and water use was expected to drop by 50–72% for the typical water use of 0.61 m^3/day (Showley, 2016). Water was recovered for irrigation, although Nexus sought to reuse water for toilets as well, which was not approved by San Diego building officials since annual inspections to certify safe use were not yet available. Similar Nexus installations were expanded to a new development by Gary McDonald Homes in Fresno, California (Fresno Bee, 2016). Most installations target new construction, but retrofits for existing homes are possible as well for \$15,000 (Showley, 2016).

NPR treatment trains 4 and 6–8 in Fig. 2 represent technologies implemented for Living Building certification (ILFI, 2017). These technologies consist primarily of natural systems for greywater treatment because full certification requires a net positive water and energy impact (amongst other requirements), and many facilities implement composting toilets to treat blackwater for fertilizer production. The Phipps Center for Sustainable Landscapes in Pittsburgh, Pennsylvania implemented NPR treatment train 4. The recycled water is used for toilet flushing; the building also harvests and treats rainwater, and they source about 24% of their water demand from the municipal water treatment plant since recycled water cannot replace potable water uses due to local and state regulations (Hasik et al., 2017). While a life cycle assessment revealed that the net-zero building (NZB, net-zero energy and water) performed better than a conventional building with a centralized water supply and wastewater treatment, the NZB actually had higher environmental impacts (10 out of 11 indicators) compared to a conventional building with low flow fixtures (Hasik et al., 2017). It should be noted, however, that the building is an education and research center that employs 40 people, so the consumption of water is relatively low and other benefits from operating such a building are not

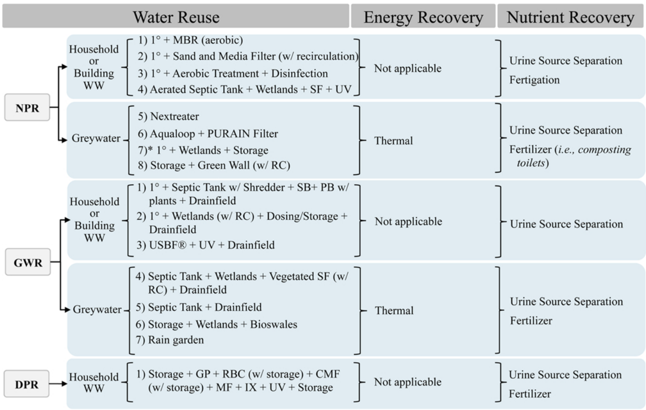

Fig. 2. Overview of resource recovery treatment trains and technologies for small-scale systems.

*Designed for all household wastewater, but treats only greywater due to the local sewer code. **Abbreviations:** 1°: primary treatment; CMF: cloth media filter; DPR: direct potable reuse; GP: grinder pump; GWR: groundwater recharge; IX: ion exchange; MBR: membrane bioreactor; MF: microfiltration; NPR: non-potable reuse; PB: purification bed; RBC: rotating biological contactor; RC: recirculation; SB: sedimentation bed; SF: sand filtration; USBF®: upflow sludge blanket filtration; UV: ultraviolet; WW: wastewater.

Table 1

Water quality guidelines and limits, and water quality achieved for small-scale case studies (Bruursema, 2011; INTEWA, 2016; BioMicrobics, 2017; ECOfluid, 2017a; ILFI, 2017; Whitelaw, 2017).

Guidelines and Technologies	Scale (m^3/day)	pH	CBOD5 (mg/L)	TSS (mg/L)	Turbidity (NTU)	*E. Coli* (MPN/100ML)
Guidelines and Limits						
NSF 350 (Residential)[a]	≤5.7	6-9	≤10	≤10	≤5	≤14
NSF 350 (Commercial)[a]	> 5.7	6-9	≤10	≤10	≤2	≤2.2
NSF 350-1[a]	NS	6-9	≤25	≤30	NS	NS
UniverCity Childcare Centre	5	NS	< 10	< 20	NS	< 400
Class of 1966 Environmental Center[b]	NS	NS	< 30	< 30	NS	NS
Technologies (treatment train from Fig. 2)						
BioBarrier (NPR-1)	1.9-5.7	NS	ND	ND	0.25	1.3
Aqualoop (NPR-6)	0.30-1.8	7.38	5^{BOD5}	2	0.57	1.0
UniverCity Childcare Centre (GWR-3)	5	6	4^{BOD}	21	NS	2

Abbreviations: BOD5: 5-day biochemical oxygen demand; BOD: biochemical oxygen demand; CBOD5: 5-day carbonaceous biochemical oxygen demand; ND: not detectable; NS: not specified; TSS: total suspended solids.

[a] NSF also recommends storage vessel disinfection of 0.5–2.5 mg/L.

[b] (GWR-4) Total nitrogen of less than 10 mg/L required.

incorporated into typical LCAs such as wellness aspects or the promotion of water consumption reduction and recycling in the community.

Several groundwater recharge examples also accomplish wastewater treatment via passive, natural systems (e.g., constructed wetlands or plant beds). In fact, wetlands were used for wastewater treatment in water reclamation projects across all scales. At the small scale, the Bullitt Center (Seattle, Washington) treats greywater from sinks and showers with constructed wetlands on the roof of the building (GWR-6) (Bullitt Foundation, 2013). Wetlands offer many advantages: they capture stormwater and help prevent flooding, can offer a sanctuary for fish and wildlife, require minimal maintenance and energy for operation, and can be designed for tertiary effluent polishing (US EPA, 2000a). The life-cycle costs of wetlands are dominated by the construction phase, but, overall, the costs are lower than mechanical treatment systems (US EPA, 2000a). Although implementation in cold climates was previously a challenge in maintaining adequate treatment, subsurface flow designs (including vertical flow) are often implemented in cold and very cold climates to circumvent the larger footprint that would otherwise be needed by free surface water projects (see Fig. 3). Subsurface flow designs are convenient for small-scale applications since they offer a smaller footprint and protect children and pets from exposure to the wastewater being treated (Sievers, 1993; Stefanakis et al., 2014). Large-scale systems are more likely to implement free surface water projects in areas with warmer climates and the available land space.

Water quality limits for two centers implementing groundwater recharge are summarized in Table 1. Although the Upflow Sludge Blanket Filtration (USBF®) technology used by the UniverCity Childcare Centre (GWR-3) is designed to treat 5 m^3/day of wastewater, most case studies presented by the systems' manufacturer can treat much larger flows ranging from 100 to 4000 m^3/day (ECOfluid, 2017b).

For direct potable reuse (DPR), effluent water quality that meets drinking water quality has been suggested (US EPA, 2012b) and several US states are in the process of developing a framework for potable reuse (WateReuse, 2018). DPR systems were implemented successfully in Colorado from 1976 to 1982 and in the International Space Station (Tchobanoglous et al., 2011). Pure Cycle Corporation patented the treatment technology represented by DPR-1 in Fig. 2 (Selby & Pure Cycle Corp., 1979), but they were discontinued since the systems became too expensive for the company to maintain (Tchobanoglous et al., 2011).

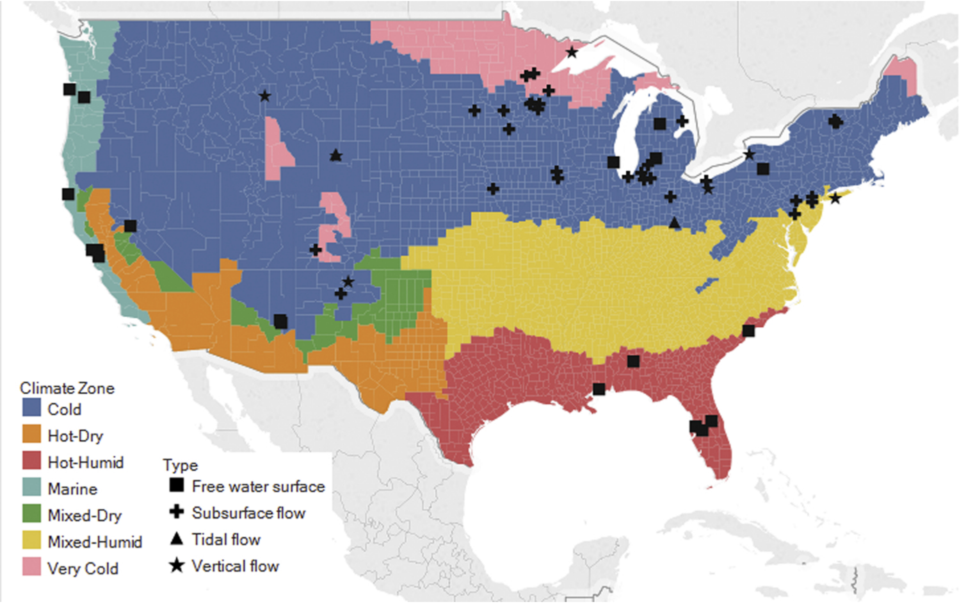

Fig. 3. Examples of wetland treatment systems in the United States mapped over climate zones. Examples sourced from Biohabitats (2019) and US EPA (1993).

3.2. Benefits

Small-scale systems offer several benefits including the potential for onsite reuse of resources, improved control of the pollutants entering the wastewater stream, and, for certain technologies, favorable life cycle impacts (see Table 2). In centralized systems, the end user of the resource can be located far away from the point of treatment, in which case transportation impacts can offset the savings from resource recovery (Lundie et al., 2004). For small-scale systems, however, there are oftentimes opportunities to recover water, energy, and nutrients for onsite use. For example, water can be recovered via onsite wastewater treatment for non-potable reuse or groundwater recharge (see Fig. 2), nutrients can be recovered via fertigation, urine source separation, or composting toilets for use on a local lawn or garden, and heat recovered from greywater can displace household energy use. Moreover, homeowners that are aware of the potentially harmful effects of disposing of hazardous pollutants "down the drain," can find safer alternatives for their disposal and improve the quality of the influent to the treatment system.

Since small-scale systems typically require more resource inputs (e.g., more infrastructure and higher energy consumption for treatment per unit of material processed) relative to large-scale systems, resource recovery scenarios for decentralized systems can result in higher environmental impacts relative to conventional, centralized systems (Shehabi et al., 2012; Cornejo et al., 2016; Hasik et al., 2017). However, life cycle studies of urine source separating technologies have exhibited lower environmental and economic impacts relative to conventional, large-scale treatment (Tervahauta et al., 2013; Ishii and Boyer, 2015). In fact, while costs were comparable for urine source separation (USS) that targeted phosphorus recovery in the study by Ishii and Boyer (2015), all estimated environmental impacts were smaller for USS and the global warming potential was almost negligible compared to centralized treatment.

3.3. Challenges

Challenges for resource recovery at the small scale consist of greater resource needs, the risk of failure or improper operation (Ursin and Roeder, 2013; Gunady et al., 2015), hindrances from local regulations for implementation (Showley, 2016), and the persistence of pharmaceuticals and personal care products following onsite treatment (Schaider et al., 2017). More resources are generally needed per unit volume of wastewater processed in smaller systems with respect to infrastructure (e.g., parallel piping for USS [Ishii and Boyer, 2015]) and energy for treatment in the case of non-passive systems (e.g., aerated designs) (Cornejo et al., 2016). Unfortunately, this also alludes to large upfront capital investments, which can be difficult for smaller parties such as homeowners to attain.

Water quality control and risk to public health are some of the greatest challenges to implement onsite treatment and reuse systems (Schoen and Garland, 2017). This is mainly due to the lower rate of dilution and the resulting higher concentration of contaminants (e.g., pharmaceuticals and heavy metals) present in the wastewater stream. Although the advanced technologies for wastewater treatment are capable of capturing a wide range of contaminants, system failures or sudden point source pollution released into the environment can result

Table 2
Overview of the benefits and challenges for resource recovery technologies at the small scale.

System Type	Benefits	Challenges	References
Household or Building Wastewater Reuse (Non-potable)	+ Onsite water reuse is feasible[a] + Lower pumping energy[a] + Less vulnerability to natural disasters and terrorism[a] *Wetlands (vs. aerobic treatment):*[a] + Lower O&M costs + Fewer energy & chemical inputs + Produce less sludge + Habitat for threatened & endangered species	- Higher treatment energy (per volume) than greywater & centralized WWT - Risk of failure or improper maintenance of treatment unit[a] - Monitoring decentralized systems is time-intensive & expensive[a] When irrigating food crops: - Presence of PPCPs post-treatment[a] *Wetlands (vs. aerobic treatment):*[a] - Design-intensive & large footprint - Accumulate nutrients & heavy metals - Higher upfront capital investment	(US EPA, 2000a; Wilderer & Schreff, 2000; Ursin and Roeder, 2013; Gunady et al., 2015; Cornejo et al., 2016; Schaider et al., 2017)
Thermal Energy	+ Onsite energy use + Less heat loss + Up to 70% water heater energy savings + Payback period ≥ 2.3 years	- Greater infrastructure needs (materials & construction required) - Higher upfront capital investment relative to no energy recovery	(Nexus, 2015; Nexus, 2017; EcoDrain, 2019)
Urine Source Separation and Composting Toilets	+ High nutrient concentration + Reduces nutrient load on wastewater treatment plants + Onsite nutrient use is feasible + Lower transportation costs and corresponding environmental impacts + Lower environmental impacts for USS (vs. centralized WWT)	- Toilets would need to be retrofit in existing buildings - Extra pipelines (when diverting urine) - Greater infrastructure needs (materials & construction) - Higher upfront capital investment relative to no nutrient recovery - Clogging & foul odor can occur - Social acceptance	(Libralato et al., 2012; Tervahauta et al., 2013; Anand & Apul, 2014; Ishii and Boyer, 2015; Landry and Boyer, 2016)
Fertigation	+ Onsite water & nutrient use + Lower pumping energy *Drip irrigation:* + Improved crop yield & water use + Saves energy & costs + Subsurface systems have fewer odor problems & improved plant uptake of phosphorus	- Higher per volume treatment energy relative to centralized WWT - Plant uptake of PPCPs *Drip irrigation:* - Limited to single plants or row crops - Surface systems are exposed to rodents, which can lead to a shorter lifespan	(Madramootoo & Morrison, 2013; Wu et al., 2015; Cornejo et al., 2016)

Abbreviations: PPCPs: pharmaceuticals and personal care products; USS: urine source separation; WWT: wastewater treatment.

[a] Similar for greywater reuse.

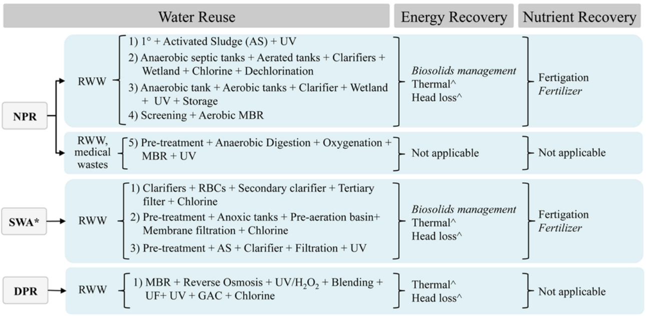

Fig. 4. Overview of resource recovery treatment trains and technologies for medium-scale systems. Italicized strategies may not necessarily be achieved simultaneously (e.g., incineration of biosolids and fertilizer production).
*These treatment trains are not intentionally for IPR, but align with the recommendations of the US EPA (2012b) of implementing advanced wastewater treatment. ˆImplementation depends on a range of factors. **Abbreviations:** 1°: primary treatment; AS: activated sludge; DPR: direct potable reuse; GAC: granular activated carbon; IPR: indirect potable reuse; MBR: membrane bioreactor; NPR: non-potable reuse; RBC: rotating biological contactor; RWW: raw wastewater; SWA: surface water augmentation; UF: ultrafiltration; UV: ultraviolet.

in a range of human health concerns, especially if they remain undetected. Because of the decentralized nature of small-scale systems, monitoring the water quality of these systems would be more time-intensive and, consequently, become more expensive than systems at larger scales. Moreover, homeowners can lack the knowledge needed to properly operate and maintain the treatment system so that it performs as designed. For example, a survey of homeowners in Northern Illinois indicated that 47.1% of homeowners (sample size of 408) did not inspect their septic systems, which is a best management practice to help mitigate non-point source pollution (Brehm et al., 2013).

The presence of emerging contaminants such as pharmaceuticals and personal care products (PPCPs) in treated wastewater is a challenge that persists across all scales. The most pertinent resource recovery scenarios that could be affected by PPCPs at the small scale are plant irrigation, fertigation, or fertilizer application due to the potential for food crop contamination. Several conditions affect PPCP uptake including the type of contaminant, plant, and transfer mechanism (hydroponics, biosolids application, wastewater irrigation of soil, etc.). The bioconcentration factor (BCF, the ratio of analyte concentration in the plant to its concentration in soil) measured in the leaf or stem was found to be highest (median of ˜7.8 to 0.9) for carbamazepine, diclofenac, propranolol, triclosan, and chloramphenicol in a review by Wu et al. (2015). In contrast, at the root, the highest BCF (median of ˜24 to 4) was found for salbutamol, triclocarban, metformin, carbamazepine, diclofenac, and triclosan (Wu et al., 2015).

3.4. Outlook

Options to improve the performance of onsite systems and lower the health risk to the final users of reclaimed water include improving homeowner knowledge of best practices (Brehm et al., 2013), allocating centralized management of onsite systems to a professional agency, and implementing real-time monitoring and control of the systems. Although there are several technologies available for real-time monitoring of physiochemical properties of waters (Cloete et al., 2016; Lambrou et al., 2014), the development of technologies capable of the continuous monitoring of contaminants (e.g., pathogens, viruses, PPCPs, heavy metals) could significantly improve the performance of onsite systems.

Emerging technologies for advanced onsite treatment can also serve to improve effluent quality. Electrocoagulation followed by ultra-filtration and advanced oxidation followed by filtration and UV disinfection appear promising (Church et al., 2015). Although reverse osmosis, nanofiltration, and electrodialysis require more energy, these processes achieve a salt rejection as high as 98–99.9% for onsite treatment (Gassie and Englehardt, 2017). Reverse osmosis, nanofiltration, and advanced oxidation processes can generally achieve a high rate of PPCP removal as well (Yang et al., 2017), although they are not common at the small scale. Their implementation and high maintenance requirements (in terms of costs and expertise) at the household-level could be challenging. Recent technologies, such as synthesized nanomaterials for heavy metals removal and vacuum membrane distillation and crystallization, have also shown good results in achieving higher water qualities, however, their implementation at the small scale seems feasible only in the case of severe water shortage, due to the complexity of the processes and high costs for installation and operation (Jia et al., 2018; Lim et al., 2018).

4. Medium-scale systems

Medium scale systems encompass facilities with a minimum capacity of 8 m^3/day and maximum flow of 20,000 m^3/day (2000 GPD to 5 MGD), which can serve a population of 20–47,000 inhabitants.

4.1. Overview

4.1.1. Energy recovery

Mature technologies for energy recovery consist of thermal energy recovery, hydraulic head loss (hydropower), and biosolids management processes (see Fig. 4). An example of a medium-scale system that implements thermal energy recovery is the Wintower building in Winterthur, Switzerland. The site sewer mines 4320 m^3/day (1 MGD) of municipal wastewater, and uses two heat exchangers and a pumping station with screening to extract a maximum of 480 kW of heat from wastewater for heating and 600 kW of heat from the building for cooling (HUBER SE, 2017). Hydropower can be captured from flowing wastewater (raw or treated) that drops in elevation. A hydroelectric plant would capture this energy with turbines and convert it to electricity. At the medium scale, hydropower is generated at the Profray plant in Bagnes, Switzerland (8600 m^3/day nominal discharge) from wastewater that has undergone pretreatment (San Bruno et al., 2010). The plant leverages a large elevation drop that amounts to a gross head of 449 m to generate 851 MWh/year (380 kW of electrical output). In contrast, La Louve in Lausanne, Switzerland is a larger plant (10,400 m^3/day nominal discharge), but it generates about half as much energy (460 MWh/year, 170 kW) since the gross head is only 180 m (San Bruno et al., 2010).

Biosolids can be leveraged for energy and nutrient recovery. Biogas production via anaerobic digestion is most commonly implemented for energy recovery. Since the biogas consists of methane, carbon dioxide, water vapor, and other trace compounds, pretreatment of the raw gas is recommended (i.e., drying and hydrogen sulfide removal). The biogas can supplement natural gas after undergoing further cleaning via pressure swing adsorption, water or chemical scrubbing, cryogenic separation, or membrane separation (Simmit, 2016). Alternatively, the biogas can be used to produce heat, electricity, and/or fuel. At the medium scale, the sludge handling process for the City of Beaver Dam's 16,000 m^3/day plant in Wisconsin stabilizes primary and secondary sludge in two anaerobic digesters (Beaver Dam, 2014, 2017). The methane produced fuels two out of four aerators for the activated sludge process.

Biosolids incineration is also common as it not only reduces the waste volume and destroys pathogens, but it also offers an opportunity for "reliable" electricity production in larger plants (Stillwell et al., 2010). Incineration can be accomplished with a multiple hearth furnace or fluidized bed furnace; thereafter, the exhaust should be cleaned to reduce odor and the emission of harmful pollutants. The heat from incineration can be used in a steam cycle power plant to produce electricity. Cartmell et al. (2006) showed that a net energy gain of 0.58

to 5.0 kWh/kg dry solids could be achieved via co-combustion or when biosolids are used in a cement kiln.

4.1.2. Nutrient recovery

Biosolids collected at WWTPs are commonly land applied in the United States to serve as a soil amendment for agriculture or land reclamation. Typically, around 20–30% of the nitrogen and 30–40% of the phosphorus from wastewater remains in sludge in conventional aerobic wastewater treatment; when enhanced phosphorus removal or precipitation is implemented, up to 95% of the phosphorus can remain in the sludge, which makes it a viable source of nutrients when land applied (Cornel et al., 2011). Biosolids can be stabilized by pH adjustment (i.e., alkaline stabilization), aerobic or anaerobic digestion, composting, or heat drying (US EPA, 2000b). Most biosolids in the US undergo anaerobic digestion; however, for smaller plants (less than 20,000 PE), aerobic digestion is more economical unless co-digesting with biowaste for energy recovery (Nowak et al., 2004). Dewatering helps reduce the volume of sludge and, consequently, transportation costs. For the Beaver Dam WWTP, the biosolids from secondary digesters (2% solids) are land applied in neighboring farms during warm months (Beaver Dam, 2014). When the land is frozen, the biosolids are dewatered by a belt filter press with polymer addition to achieve 12% solids concentration for onsite storage.

The Delhi Charter Township WWTP in Michigan has a capacity of 15,000 m^3/day (4.0 MGD) and implements energy and nutrient recovery (Viswanathan, 2010; Delhi, 2018). Its biosolids handling capacity was increased from 45 to 114 m^3/day (12,000 to 30,000 GPD) in 2007 and incorporated parallel treatment trains of two-phased anaerobic digesters that were capable of advanced, high-rate processing. The biosolids handling system consists of thermophilic (55 °C) and mesophilic digestion (37 °C). Additionally, two 30 kWh microturbines were installed for combined heat and power. Since the microturbines have an electrical efficiency of about 30%, the primary form of energy generated is heat. Nonetheless, the system can reduce electricity requirements by more than 40% and eliminate nearly all outsourced process heat. Class A biosolids are produced, for which enteric virus and helminth ova must be monitored (Viswanathan, 2010).

4.1.3. Water reuse

With respect to water reuse, NPR treatment systems can generally be classified into activated sludge (conventional systems), wetlands (natural systems), and membrane bioreactor (MBR)-based treatments (see Fig. 4). The Porlock WWTP in the United Kingdom (NPR-4 in Fig. 4) and Whitecap WWTP (NPR-1) in Texas are examples of facilities implementing such treatment systems and the water quality these facilities achieve are presented in Table 3. Oregon Health & Science University's wastewater system in the US (POSD, 2007) is another successful implementation of a medium-scale MBR system (NPR-5). The effluent water quality reaches Class 4 standards (near drinking water quality) and the effluent water is used for toilet flushing, cooling towers, and landscape irrigation. Detailed treatment trains for medium-scale systems are available in Section 3.1 of the Appendix.

Indirect Potable Reuse (IPR) projects incorporate an environmental buffer before further treatment at a water treatment plant for potable water reuse. The environmental buffer typically consists of groundwater recharge or surface water augmentation, and may serve multiple purposes such as: improving public perception by adding a natural component to the reclaimed water process, decreasing the concentration of contaminants (e.g., through attenuation processes), diluting the reclaimed water, and increasing the length of time between the reclaimed water's production and use (NRC, 2012).

IPR treatment trains were not explicitly found at the medium scale, but treatment trains SWA-1 through SWA-3 (see Fig. 4) align with the recommendations of the US EPA (2012b) of implementing advanced wastewater treatment. These treatment trains include rotating biological contactors (RBCs), tertiary filtration, and/or membrane filtration (see Fig. 4). A notable example is Fennimore WWTP in Wisconsin. The plant utilizes RBCs to develop biofilms for biochemical oxygen demand (BOD) removal. The final units in the contactors have biofilms containing nitrifying bacteria capable of removing ammonia from the wastewater (Town and Country Engineering, Inc., 2015). The effluent from secondary clarifiers following RBCs is further treated in tertiary filters for the additional removal of suspended solids and reduction of organics. Tertiary filters are designed to backwash cells using an air/water scour system, and the effluent from the filters flows to a clear well and eventually to a chlorine contact chamber (see Table 3 for water quality characteristics).

Cloudcroft WWTP in New Mexico with a capacity of 379 m^3/day (0.1 MGD) is one of the best early-stage examples of DPR at the medium scale. Dramatic increases in population during weekends make it difficult for the mountain community to meet potable water demands solely with its spring and well supplies (Tchobanoglous et al., 2011). The treatment train is illustrated in Fig. 4 (DPR-1), and can be described as an advanced wastewater treatment train combined with an advanced drinking water treatment train (Gerrity et al., 2013).

4.2. Benefits

As the system scale increases, economies of scale generally reduce the energy consumed per unit of wastewater (EPRI and WRF, 2013) or biosolids (Soda et al., 2010) processed. While there is some overlap between the wastewater treatment processes used at the medium scale and those at the small and large scales, one of the most promising technologies that has been used for medium-scale facilities is the MBR. MBRs have been shown to be a highly effective treatment process when a high-quality effluent or the growth of specialized bacteria (e.g., nitrifiers) is needed (Gander et al. 2000; Severn, 2003; Melin et al., 2006) and offer a relatively small footprint for treatment. The energy and

Table 3

Water quality for medium-scale, non-potable reuse (Severn, 2003; City of Corpus Christi, 2013) and surface water augmentation (CH2M HILL, 2010; Water Environment Association of Texas, 2010; Town and County Engineering, Inc. 2015) facilities.

Case Studies	**Capacity ($10^3 m^3$/ day)**	**COD (mg/L)**	**TSS (mg/L)**	**TN (mg/L)**	**TP (mg/L)**	**Turbidity (NTU)**	**Fecal (coli/100ML)**
Non-Potable Reuse (location, treatment train from Fig. 4)							
Porlock (UK, NPR-4)	2	< 4	< 1	< 1	NS	0.23	7.3
Whitecap, Texas (US, NPR-1)	9.5	6^{BOD5}	7	3.5	2.2	NS	11
Surface Water Augmentation (SWA) (location, treatment train from Fig. 4)							
Fairview City, Utah (US, SWA-2)	1.4	NS	NS	10	1.0	NS	NS
Fennimore, Wisconsin (US, SWA-1)	2.3	NS	NS	NS	0.72	NS	NS
Peninsula WRP, Texas (US, SWA-3)	3.6	ND	ND	0.2	0.5	NS	NS

Abbreviations: BOD: biochemical oxygen demand; BOD5: 5-day biochemical oxygen demand; COD: chemical oxygen demand; ND: not detectable; NS: not specified; TN: total nitrogen; TP: total phosphorus; TSS: total suspended solids; WRP: water reclamation plant. **Country Abbreviations:** UK: United Kingdom; US: United States.

nutrient recovery methods are similar for medium- and large-scale systems, and they accordingly share many benefits such as waste volume reduction via biosolids incineration and the slow release of nutrients from fertilizer produced from biosolids. A summary of the benefits associated with medium- and large-scale resource recovery systems is provided in Table 4.

4.3. Challenges

Challenges at the medium scale include the high energy consumption of certain treatment processes, the higher risk of failure relative to more centralized facilities, the lack of operator expertise, the removal and crop uptake of PPCPs, and the need to be in close proximity to the end user of the resource being recovered (see Table 4). The energy-intensive nature of aerobic MBRs and fouling control processes can lead to high costs and environmental loads (Krzeminski et al., 2017). Full-scale municipal MBRs consume about 0.4–3.0 kWh/m^3, however, optimization strategies have been able to bring energy consumption down to 0.37–0.5 kWh/m^3 (Krzeminski et al., 2017) and several pilot-scale anaerobic MBRs have exhibited the potential to be net energy producers (Shin and Bae, 2018).

The smooth operation of smaller medium-scale WWTPs is often difficult to maintain. In a case study of small WWTPs in southeast England, the most common causes of compliance failures were found to be hydraulic overloading, biological and tertiary problems, organic overloading, high retention, plant deficiencies, and contractors (Rowland and Strongman, 2000). Smaller plants also run the risk of producing biosolids with higher concentrations of hazardous substances

Table 4
Overview of the benefits and challenges for resource recovery technologies at the medium and large scales.

System Type	Benefits	Challenges	References
Non-Potable Reuse (NPR)	+ Remote control of smaller WWT plants is possible + Larger scales result in lower treatment energy and costs per volume treated *Membrane Bioreactors:*[a] + Highly effective treatment process + Small footprint *Wetlands (vs. conventional WWT):* + Lower operation and maintenance costs + Less energy and chemical inputs + Produce less sludge + Habitat for threatened & endangered species	- Higher risk of failure, lack of trained operators, and less dilution of harmful substances for smaller WWT plants - Diseconomies of scale in collection & distribution - High distribution energy (relative to onsite) - Vulnerability to natural disasters and terrorist attacks *Membrane Bioreactors:*[a] - Aerobic systems are energy intensive - Membrane fouling and replacement costs *Wetlands (vs. conventional WWT):* - Design-intensive, large footprint, and high capital costs - Accumulate nutrients and heavy metals	(Gander et al., 2000; Severn, 2003; Melin et al., 2006; McCarty et al., 2011; Libralato et al., 2012; Winans et al., 2012; EPRI and WRF, 2013; Guo et al., 2014; Krzeminski et al., 2017; Schaider et al., 2017; Yang et al., 2017)
Indirect and Direct Potable Reuse	+ Larger scales result in lower treatment energy per volume treated + Avoid parallel distribution pipeline *Reverse osmosis:* + High quality effluent produced (e.g., PPCP removal)	- Higher treatment energy (vs. NPR) - Public opposition for direct potable reuse *Reverse osmosis:* - Energy intensive - Brine disposal difficult in inland areas	(EPRI and WRF, 2013; Millan et al., 2015; Yang et al., 2017)
Thermal Energy	+ Represents the largest quantity of energy that could be recovered from wastewater + Heat can be used onsite (e.g., to heat digesters)	- Flow rate should be ≥ 1300 m^3/day - Heat demand should be ≥ 100 kW - Need high performance heat pumps, and close proximity between heat source and sink	(Müller and Butz, 2010; McCarty et al., 2011)
Hydropower	+ No onsite emissions from energy generation	- Requires high enough flow rate and elevation drop	(Chae and Kang, 2013; Power et al., 2014)
Biosolids Management	*Biogas production (anaerobic digestion):* + Treatment is less energy-intensive than aerobic digestion + Facilitates energy self-sufficiency at the plant *Incineration for energy recovery:* + Reduces waste volume and destroys pathogens + Co-combustion shows higher energy recovery potential *Fertilizer production for land application:* + Reduces presence of nutrients in treated effluent + Slow release of nutrients vs. commercial fertilizer (reduces likelihood of leaching/contamination of water) + Inexpensive vs. other biosolids management solutions + Struvite production: concentrated fertilizer is produced (lowers transportation costs), and hazardous metal content found to be below limits for commercial fertilizer	*Biogas production (anaerobic digestion):* - Feasible at higher scales *Incineration for energy recovery:* - Effective dewatering and short transportation distances needed (process could be energy neutral or an energy sink) - Close proximity to end user of heat needed *Fertilizer production for land application:* - Close proximity to farmlands needed - Public opposition near residential areas - Risk of high concentrations of hazardous substances - Alternative use or storage necessary when conditions prevent land application - Uptake of PPCPs by crops being fertilized - Phosphorus recovery from the liquid phase can be low in pilot/full-scale implementations (≤ 25% for some technologies)	(US EPA, 2000b; Ueno and Fujii, 2001; Cartmell et al., 2006; Soda et al., 2010; Gu et al., 2017; Amann et al., 2018)
Fertigation	+ Facilitates water and nutrient recovery + Lower WWT requirements since nutrients are preserved + Lower energy and chemical requirements for treatment	- Higher pumping energy requirements (vs. onsite) - Farmlands need to be within relatively close proximity (difficult in urban areas) - Uptake of PPCPs by crops being irrigated	(EPRI and WRF, 2013; Wu et al., 2015)

Abbreviations: PPCPs: pharmaceuticals and personal care products; WWT: wastewater treatment.

[a] Applies to indirect and direct potable reuse as well.

Table 5

Case studies of energy recovery technologies at the higher medium and large scales (Kalogo et al., 2008; MWRA, 2009; Patneaude, 2010; San Bruno et al., 2010; Bravo and Ferrer, 2011; Market Wired, 2011; Brown and Caldwell, 2012; MWRA, 2013; Danfoss, 2014; Gikas, 2014; Power et al., 2014; SD Public Utilities, 2015; Karáth, 2016; HUBER SE, 2017; City of San Diego 2017a, b, c; Aarhus Vand, 2019; Mikkonen et al., 2019). Results for hypothetical case studies and additional experimental data are available in the Appendix.

Type	Case Study	Capacity ($10^3 m^3$/ day)	Energy Input	Energy Output	Net Energy	Units	Notes
Anaerobic digestion	Marselisborg (DK)	200^{PE}	6311	9628	3317	MWh/year	2015 energy input and production
	Point Loma (US)	908	691	788	96	ML gas/year	Gas input for boilers, burners, & GUF
	Baix Llobregat (ES)	270	61^{ELEC} 11^{NG} [a]	55^{ELEC}		kWh/m^3 Nm^3/m^3	Electricity and natural gas input is shown per m^3 of thickened sludge for wastewater and sludge treatment
	Deer Island (US)	3400 + 1400	$158^{P,ELEC}$ [c]	28^{ELEC}		GWh/year	Heat value: $10-15 M/year
	Metro Biosolids Center (US) [b]	Large	100,313	102,751	2,438	ML gas/year	Gas input for flares and cogeneration
Pyrolysis/ Gasification	Balingen (DE)	27^{T}	0.1^{GAS}	0.6	0.5	kWh/kg TS	0.1 kWh/kg TS of output is heat; Operates at 900 °C
	Munich (DE)	Large^{TB}	3.6	8.9	5.2	MJ/kg PFSS	Max temp: 950-1050 °C
Hydraulic head loss	Deer Island (US)	3400 + 1400	$158^{P,ELEC}$ [c]	> 6		GWh/year	Head: 3.96-10.1 m; Cost: 2923 €/kW
	Point Loma (US)	908		1.35		MW	Head: 27.4 m; Cost: 649 €/kW
	Bagnes (CH)	8.6^{DIS}		851		MWh/year	Head: 449 m; Cost: €375k
	Lausanne (CH)	10^{DIS}		460		MWh/year	Head: 180 m; Cost: €430k
	Seefeld Zirl (AT)	21.6^{DIS}	2000	5,500	3,500	MWh/year	Head: 625 m; Cost: €2.2M
	Nyon (CH)	25^{DIS}		700		MWh/year	Head: 94 m; Cost: €500k
Thermal	Winterthur (CH)	4.32^{PT}		480-600		kW	Wintower building
	Hammarbyverket (SE)	$96\text{-}432^{T}$		$1{,}235^{Heat}$		GWh/year	Heat use: 95,000 buildings
	Sandvika, Oslo (NO)	259^{T}		20^{Heat} 18^{Cool}		MW MW	4 °C temperature drop for heating; nominal capacities are shown

Abbreviations: DIS: nominal discharge; ELEC: electricity consumed or produced; GAS: energy needed for the gasification process; GUF: gas utilization furnace; NR: not reported; P: energy input for the WWTP; PE: 10^3 persons-equivalent; PFSS: primary fine sieved solids; PT: pretreated wastewater; T: treated wastewater flows; TB: testbed; TS: total solids. **Country Abbreviations:** AT: Austria; CH: Switzerland; DE: Germany; DK: Denmark; ES: Spain; NO: Norway; SE: Sweden; US: United States.

[a] Natural gas supplements the biogas.

[b] Processes methane from a neighboring landfill as well.

[c] Calculated based on the assumption that 18 MW of electricity is demanded 24 hours a day and 365 days a year.

if dilution with more conventional waste streams is not achieved. The wastewater industry as a whole is experiencing a deficiency in the available technical expertise needed to operate plants, and the gap is expected to grow as experienced personnel retire (Brueck et al., 2012). Unfortunately, these challenges can be compounded in developing countries where resources and operator training are limited (Cossio et al., 2018).

4.4. Outlook

The implementation of real-time process monitoring can assist in lowering the rate of compliance failure significantly (Rowland and Strongman, 2000). Most recently, an intelligent monitoring system that implements a soft sensor technique (leveraging a fuzzy neural network) has shown accuracies of 90% and above in the monitoring of total phosphorus and ammonia nitrogen when tested at full-scale WWTPs (Han et al., 2018). In another example, the utilization of UV–Vis spectroscopy with data analytics has been shown to serve as a mechanism for anomaly detection in WWTPs (Chow et al., 2018). Such advancements in sensor technologies and techniques for data mining and analytics can help transform large, complex datasets into actionable information for plant operators.

5. Large-scale systems

Large-scale systems in this review paper are treatment plants with flows of more than 3800 m^3/day (1 MGD), which serve 9090 people or more.

5.1. Overview

5.1.1. Energy recovery

While the vast majority of energy recovery solutions provide a portion of the energy needed for wastewater treatment, at the large scale, energy self-sufficiency and net positive energy production can be achieved. WWTPs that have achieved or are close to achieving energy self-sufficiency rely primarily on anaerobic digestion (Gu et al., 2017). The Marselisborg WWTP in Denmark, for example, invested €3 M to optimize its treatment processes and enhance biogas production from onsite digesters (Karáth, 2016). The improvement in energy efficient processes and equipment resulted in significant headway, as the plant generated more than 150% of its energy requirements (Danfoss, 2014; Aarhus Vand, 2019). In another example, the Point Loma WWTP in San Diego, California implements anaerobic digestion and hydropower generation to fuel its wastewater treatment process and sells excess energy to the electrical grid (City of San Diego, 2018). Engine heat from the cogeneration plant is recycled onsite to heat the plant's digesters. At the nearby Metro Biosolids Center (MBC), primary and secondary sludge are transformed to a cake of 30% solids by degritting, centrifuge thickening, anaerobic digestion, storage and mixing with Point Loma's biosolids, and dewatering (City of San Diego, 2017a). The MBC's cogeneration facility receives methane from its on-site digesters and a neighboring landfill, and produces an average of 6.4 MW of power (City of San Diego, 2017b). A summary of the energy output for several case study plants is shown in Table 5.

5.1.2. Nutrient recovery

The Watsonville Area Water Recycling Project in California facilitates nutrient and water recovery via fertigation by implementing treatment train NPR-4 (see Fig. 5) in a tertiary treatment facility (29,000 m^3/day capacity). Approximately 27.4 mg/L of total nitrogen (Lockwood, 2018) are retained in the water for use on farmland (see Table 6 for additional water quality parameters). By replenishing a portion of the groundwater that gets pumped for agriculture, the project also helps combat seawater intrusion. Secondary treatment is achieved offsite and costs roughly $1.62 per m^3; tertiary treatment (operation and maintenance) and delivery costs amount to approximately $0.49 per m^3 (Lockwood, 2018).

Based on a review by Egle et al. (2015), about 50 technologies can recover phosphorus (P) from wastewater and its treatment byproducts (e.g., digester supernatant, sewage sludge, sewage sludge ash) including crystallization, precipitation, wet chemical processes, and thermo-chemical processes. When P is recovered from the liquid phase (e.g., from wastewater treatment effluent, supernatant liquor, and sludge liquor), a P recovery rate of up to 50–94% can be achieved (Cornel and Schaum, 2009; Rahman et al., 2014). Many crystallization and precipitation processes have been developed or commercialized including PhoStrip, PRISA, DHV Crystalactor, CSIR, Kurita, Ostara, Phosnix, Berliner Verfahren, and FIX-Phos (Mehta et al., 2015). In 2016, Ostara and the Metropolitan Water Reclamation District of Greater Chicago opened the world's largest nutrient recovery facility for a project cost of $31 M (Hawthorne, 2016). The Stickney WWTP is expected to produce up to 10,000 tons of fertilizer a year, generate $2 M of revenue a year, and reduce phosphorus discharges by 30%. Ostara augments conventional biological nutrient removal processes with its Waste Activated Sludge Stripping to Remove Internal Phosphorus (WASSTRIP®) and Pearl® technologies. The technologies offer many benefits including a reduction in sludge production, up to 50% P removal, and a revenue stream with the sale of Crystal Green®, a slow release 5-28-0 fertilizer. As of 2017, the Ostara technology had 15 commercial installations located in the US, Canada, the Netherlands, Spain, and the United Kingdom (Ostara, 2017).

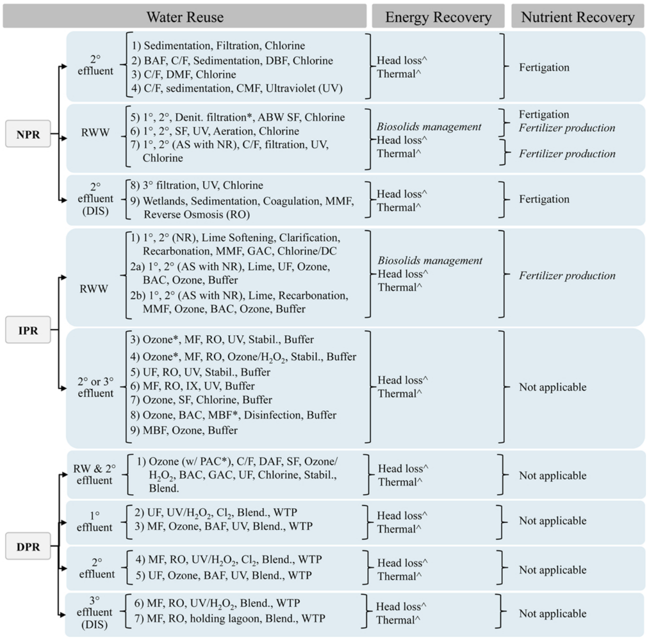

Fig. 5. Overview of resource recovery treatment trains and technologies for large-scale systems. Strategies that are italicized mean that the energy and nutrient recovery options may not necessarily be achieved simultaneously. *Processes are included in some locations or instances. ^The implementation of the technology also depends on other factors. **Abbreviations:** 1°: primary treatment; 2°: secondary treatment; 3°: tertiary treatment; ABW: Automatic backwash; AS: activated sludge; BAC: biological activated carbon; BAF: biologically aerated filtration; Blend.: blending; C/F: coagulation and flocculation; CMF: cloth media filtration; DAF: dissolved air flotation; DBF: deep bed filtration; DC: dechlorination; DIS: disinfected; DMF: dual-media filtration; DPR: direct potable reuse; GAC: granular activated carbon; GAS: gasification; HEX: heat exchanger; HYP: hypothetical; INC: incineration; IPR: indirect potable reuse; IX: ion exchange; MBF: membrane filtration; MF: microfiltration; MMF: multi-media filtration; NPR: non-potable reuse; NR: nutrient removal; PYR: pyrolysis; RO: reverse osmosis; RW: raw water; RWW: raw wastewater; Stabil.: stabilization; SF: sand filtration; WTP: water treatment plant; UV: ultraviolet.

Table 6
Water quality guidelines and outcomes for large-scale non-potable reuse (Pinellas County, 2015; Crook, 2007; Denver Water, 2016a, b; City of Watsonville, 2018; Lockwood, 2018; Pinellas County, 2019), indirect potable reuse (Asano et al., 2007; Gerrity et al., 2013; CDPH, 2014; PUB, 2017a, b; OCWD, 2019a), and direct potable reuse case studies (Lahnsteiner & Lembert, 2007; Menge, 2007; Steinle-Darling et al., 2016).

Guidelines and Case Studies (location, treatment train from Fig. 5)	Capacity ($10^3 m^3$/ day)	COD (mg/L)	TSS (mg/L)	TN (mg/L)	TP (mg/L)	Turbidity (NTU)	Pathogens
Non-Potable Reuse (NPR)							**Fecal (coli/100 ML)**
Denver, Colorado (US, NPR-2)	114	$4\text{-}8^{TOC}$	NS	5-30	0.04-0.4	0.15	< 1
Watsonville (US, NPR-4)[a]	29	$3.4\text{-}14.5^{BOD}$	NS	27.4	$< 0.1^{OP}$	1.28	< 2
South Cross Bayou (US, NPR-5)	125	NS	NS	0.96^{NO3}	0.27	NS	NS
William E. Dunn (US, NPR-5)	34	NS	NS	1.77^{NO3}	0.22	NS	NS
South Cary (US, NPR-6)	48	0-0.2	0.8-2.1	1.8-3.6	0.4-2.1	NS	1-9
Indirect Potable Reuse (IPR) Guidelines							**Log Reduction**
California[b]	–	$< 0.5^{TOC}$		< 10			$12^{Enteric}$; $10^{Giardia}$; $10^{Crypt.}$
IPR Case Studies							**Fecal (coli/100 ML)**
Fairfax County (US, IPR-1)	204	10	0.3[c]	$< 1.0^{TKN}$	> 99%[d]	< 0.3[c]	NS
GWRS (US, IPR-3)	378	0.16^{TOC}	54^{TDS}	1.8	$< 0.01^{PO4}$	0.05	< 2
NEWater (SG, IPR-3)	644	$< 0.5^{TOC}$	$< 150^{TDS}$	$< 11^{NO3}$	NS	< 5	$< 1^{Ecoli}$
Direct Potable Reuse (DPR) Guidelines							**Fecal (coli/100 ML)**
Namibian Guideline	–	NS	1005^{TDS}	10^{NO3}	NS	NS	NS
Reclamation Standard 2002	–	10	1000^{TDS}	10^{NO3}	NS	NS	NS
New Goreangab^{GV}	–	20	NS	NS	NS	0.1	ND^{Ecoli}
DPR Case Studies							
New Goreangab (NA, DPR-1)	21	11	1072^{TDS}	20^{NO3}	NS	0.09	0
Big Spring, Texas (US, DPR-6)	7.6	NS	NS	$\leq 0.01^{NH3}$	NS	≤ 1.16	ND^{Ecoli}

Abbreviations: COD: chemical oxygen demand; GV: guarantee values; GWRS: Orange County's Groundwater Replenishment System; ND: not detectable; NS: not specified; OP: orthophosphate as phosphorus; TDS: total dissolved solids; TKN: Total Kjeldahl Nitrogen; TN: total nitrogen; TP: total phosphorus; TOC: total organic carbon; TSS: total suspended solids. **Country Abbreviations:** NA: Namibia; SG: Singapore; US: United States.

[a] The range of BOD represents bi-weekly samples from April to June 2018, the remaining values represent the average 2017 water quality.

[b] Must meet drinking water maximum concentration limits.

[c] Measured after the multi-media filtration process.

[d] Percent removal.

5.1.3. Water reuse

The treatment trains used for NPR applications are very diverse due, in part, to lower water quality guidelines or requirements, the large range of end uses, and the high frequency at which NPR projects are implemented. Typical unit processes following secondary treatment include filtration and disinfection (see Fig. 5), which coincides with the US EPA's (2012b) water reuse guidelines. The following are examples of NPR facilities:

- The Green Acres Project (GAP) of Orange County, California, treats secondary effluent from the Orange County Sanitation District via NPR-3 in Fig. 5 (OCWD, 2019b). The treatment plant has a design capacity of 28,400 m^3/day (7.5 MGD), the annual demand for GAP water in the 2014–2015 fiscal year amounted to 14,600 m^3/day (3.86 MGD) (OCWD, 2019b), and operation and maintenance (O&M) costs amounted to \$0.40 per m^3 (Water Issues Committee, 2016).
- The South Cross Bayou Water Reclamation Facility (WRF) (NPR-5 in Fig. 5 with denitrification filtration) recovers water, energy, and nutrients (Pinellas County, 2013, 2017). Reclaimed water is distributed to communities primarily for irrigation. The methane gas recovered from the digestion process partially fuels the dryer process for biosolids to produce fertilizer pellets.
- The William E. Dunn WRF in Pinellas County, Florida applies treatment train NPR-5 without denitrification, so the nitrate concentration of the effluent is subsequently higher (see Table 6). The plant operates with an average daily flow of 24,600 m^3/day (6.5 MGD) and treatment costs amount to \$0.53 per m^3 (Pinellas County, 2013, 2019).
- The Baix Llobregat WWTP in Barcelona, Spain has a capacity of 2 million PE and treats approximately 270,000 m^3/day of wastewater and 4000 m^3/day of sludge (Bravo & Ferrer, 2011). The WWTP's treatment train is based on conventional activated sludge with nutrient removal, and 30% of the secondary effluent undergoes tertiary treatment for agricultural reuse (NPR-7) and to create a seawater intrusion barrier (after additional treatment processes).

With respect to IPR projects, the Millard H. Robbins, Jr. WRF in Fairfax County, Virginia relies on activated carbon (IPR-1 in Fig. 5) to augment the Occoquan Reservoir. The project was motivated by rapid growth that led to an increase in water demand and the decline of the reservoir's water quality. Typically, 5%–8% of the inflow of the reservoir is reclaimed water, but the inflow of reclaimed water can increase to 90% during a long drought (Asano et al., 2007; Gerrity et al., 2013).

A common treatment train for IPR projects is secondary treatment followed by the implementation of ultra/microfiltration, RO, and UV light (see Fig. 5). Reverse osmosis has been used in numerous water reclamation facilities because of its ability to remove a wide array of undesirable contaminants such as bacteria, viruses, heavy metals, nitrate, and pesticides (PUB, 2016a, b; Warsinger et al., 2018). Singapore's NEWater plants (treatment train IPR-3) meet 40% of Singapore's total water demand (1.63 million m^3/day or 430 MGD) (PUB, 2017a). NEWater is added to reservoirs for IPR and is also reused in industrial and commercial buildings (PUB, 2016b). Orange County's Groundwater Replenishment System (treatment train IPR-3) is the largest system in the world for potable reuse (OCWD, 2019a). The 378,000 m^3/day (100 MGD) Advanced Water Purification Facility (AWPF) treats secondary effluent from the Orange County Sanitation District at capacity. Approximately 70% of the product water recharges groundwater using spreading ponds (basins) in Anaheim, California, which is blended with stormwater and imported/purchased water (OCWD, 2019a). When the systems' capacity was 265,000 m^3/day, water was produced at a unit cost of \$0.56/m^3 (capital and O&M) and conveyance costs amounted to an additional \$0.10/m^3 (Raucher & Tchobanoglous, 2014).

The most well-known, large-scale DPR example is the New Goreangab Water Reclamation Plant (NGWRP) in Windhoek, Namibia

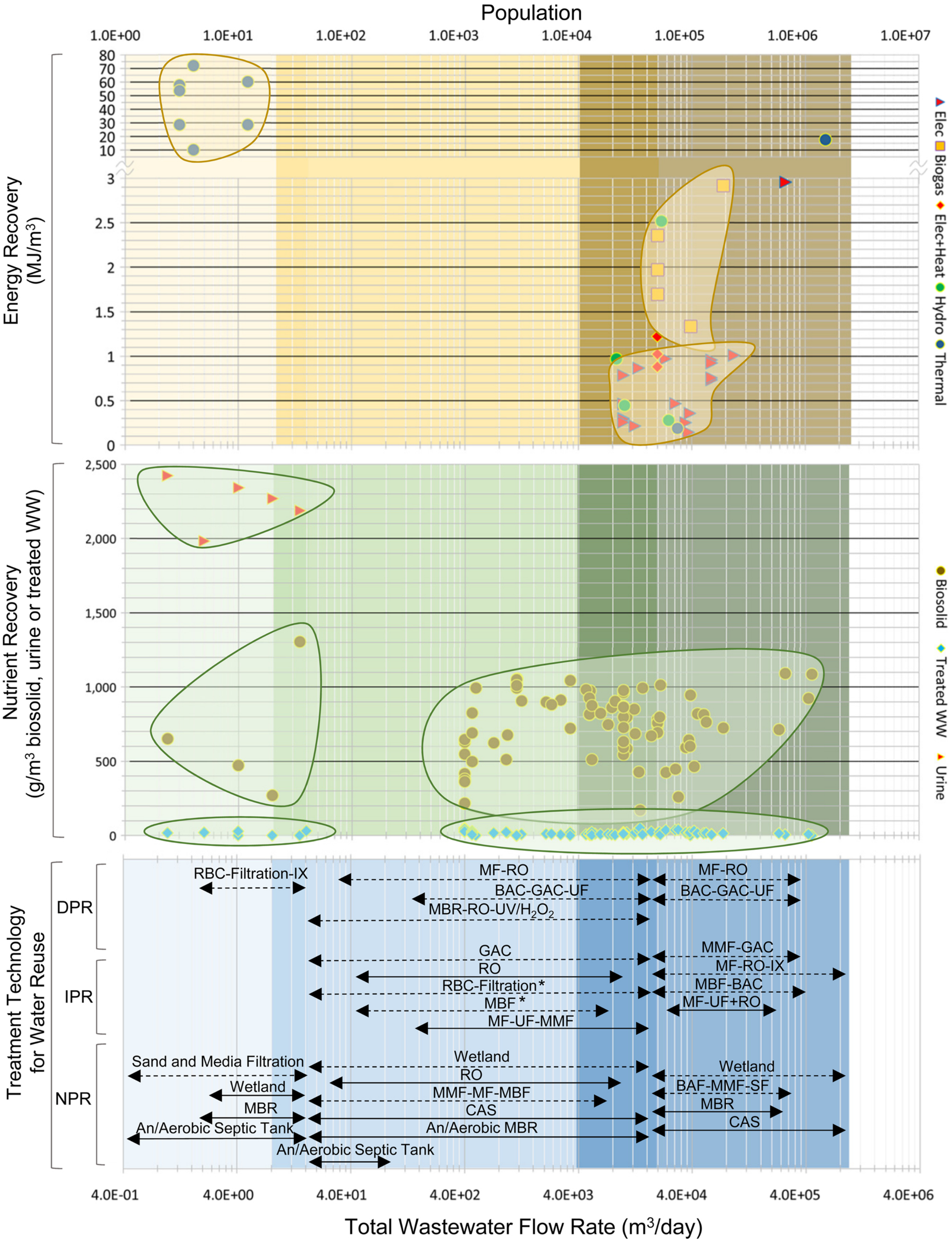

Fig. 6. Resource recovery technologies versus wastewater treatment plant scale (as proposed in this study). For the water reuse treatment options, only the main unit processes are shown and dashed lines represent technologies without information regarding scale, which mainly came from hypothetical studies.
*These examples are not intentionally for IPR, but align with the recommendations of the US EPA (2012b) of implementing advanced wastewater treatment. **Abbreviations:** BAC: biological activated carbon; CAS: conventional activated sludge; DPR: direct potable reuse; GAC: granular activated carbon; IPR: indirect potable reuse; IX: ion exchange; MBF: membrane filtration; MBR: membrane bioreactor; MF: microfiltration; MMF: multi-media filtration; NPR: non-potable reuse; SF: sand filtration; RBC: rotating biological contactor; RO: reverse osmosis; UF: ultrafiltration; WW: wastewater.

(DPR-1). As of 2007, the plant produced approximately 25% of the potable water demand for Windhoek (Lahnsteiner and Lempert, 2007). Treatment costs during the first year amounted to $0.46/m^3$ (USD 2002/3); with capital costs, the total costs amounted to $0.77/m^3$ (USD 2002/3) (du Pisani, 2006). Guarantee values for water quality (see Table 6) were based on the 1993 World Health Organization Guidelines, the 1996 Rand Water (South Africa) Potable Water Quality Criteria, and the Namibian Guidelines for Group A water (Namibia DWA, 1988).

In the US, two DPR facilities opened in Texas between 2013 and 2014. First, a $14 M facility opened in Big Spring, Texas in 2013 (Martin, 2014). The plant supplements the water supply from lakes and reservoirs along the Colorado River since the region had limited options – lacking space for new surface reservoirs and facing high evaporation rates, which made IPR impractical (Martin, 2014). The treatment train relies on microfiltration and RO as summarized by DPR-6 in Fig. 5. During the blending process, 20% reclaimed water and 80% raw surface water is used before being sent to five water treatment plants for further treatment. Effective pathogen and virus removal were shown in initial testing of one of the water treatment plants (*Cryptosporidium*, *Giardia*, enteric virus, and *E. coli* were not detectable) (Sutherland et al., 2015). A second DPR facility opened in Wichita Falls, Texas in 2014, which also relied on microfiltration and reverse osmosis for treatment (DPR-7). The project operated for ~12 months for emergency water during a drought, and the city planned to transition to IPR with surface water augmentation (SWRCB, 2016). Additionally, treatment trains DPR-2 to DPR-5 were included in Fig. 5 as they are recommended DPR treatment trains (Trussell et al., 2015).

5.2. Benefits

As highlighted in Table 4, large-scale systems benefit from lower costs and energy consumption for the treatment of wastewater and biosolids, in addition to improved process efficiencies for electricity generation from combined heat and power (CHP). For CHP specifically, plants of more than 100,000 PE can achieve a ratio of 0.68 to 1.5 of electricity generated versus electricity used by the plant, whereas a ratio of 0.37 is expected for smaller plants of less than 10,000 PE (Bachmann, 2015; Aarhus Vand, 2019). This is likely why energy recovery projects via the anaerobic digestion of biosolids are prevalent at the large scale. Other benefits at the large scale are specific to the technology implemented. For example, reverse osmosis has been shown to effectively remove PPCPs (Yang et al., 2017), land applied biosolids release nutrients more slowly than commercial fertilizers (reducing the likelihood of nutrients contaminating groundwater or surface waters) (US EPA, 2000b), and biosolids incineration results in less waste and effectively destroy pathogens. Refer to Table 4 for additional benefits at the large scale.

5.3. Challenges

The major challenges at the large scale include the high energy consumed to distribute reclaimed water, public opposition, vulnerability to natural disasters and terrorist attacks, in addition to the feasibility constraints for thermal energy recovery, hydropower generation, the land application of biosolids, and fertigation. Public opposition is most relevant for DPR and biosolids management. Although a public perception study in California showed a strong majority supported expanding water reuse activities (94% of participants), direct potable reuse still faces opposition as most participants found drinking reclaimed water unacceptable (54% of participants) (Millan et al., 2015). Fortunately, messaging and education play a key role and provide an opportunity to sway participants' perception of potable reuse. The land application of biosolids also faces public opposition, especially when applied near residential areas (US EPA, 2000b). Other major challenges include the need for storage or alternative uses when land application is not feasible, the proximity to farmlands in urban cities, and stricter regulations limiting their end use or disposal. For example, although seawater disposal of biosolids was prevalent in Europe, it was banned in 1998 to protect the aquatic environment (Roy et al., 2011). In New Zealand, "landfilling…is becoming increasingly difficult as a result of reduced land availability, increasing compliance costs, public opposition, and leachate and greenhouse gas emission concerns" (Wang et al., 2008).

While larger systems require less treatment energy per unit volume of wastewater (Guo et al., 2014), pumping energy requirements for wastewater collection and reclaimed water distribution can overshadow these savings from economies of scale. With respect to water reuse applications, the reclaimed water produced in large-scale systems is primarily applied to NPR applications (e.g., agricultural irrigation, industrial, groundwater recharge, and environmental reuse) (Chen et al., 2017; Matos et al., 2014). The end user of the reclaimed water can be located far away from the WWTP, thus increasing the overall energy consumed for the water system significantly. The energy intensities of water pumping systems are location-specific and depend on a variety of factors such as the grade of the pipeline system and topography of the area (Plappally & Lienhard, 2012). Several studies have shown that when long distance water transfer applies to the reuse scenario, the pumping energy is responsible for the majority of the costs and environmental impacts associated with the water system (Rezaei et al., 2018).

5.4. Outlook

The challenge of distributing reclaimed water in large water networks can be overcome by sewer mining. The approach provides a variety of feasible alternatives for wastewater treatment and reuse, and eliminates the extra costs associated with long-distance water transfers. Australia pioneered the approach and several successful applications have been shown for non-potable urban reuse with capacities ranging from 100-2,200 m^3/day (Makropoulos et al., 2018). For example, the sewer mining technology in Flemington, Australia treats 100 m^3/day of wastewater for irrigation using a dual membrane system and UV disinfection (Waste Technologies of Australia, 2006). Other treatment technologies consist of a septic tank followed by filter beds and UV, a moving bed biofilm reactor followed by RO and UV, a sequencing batch reactor with nutrient removal, and MBR followed by UV (Makropoulos et al., 2018).

With growing populations and stricter regulations for landfilling and the land application of biosolids, emerging technologies to reduce the volume of waste (pyrolysis/gasification), create commercial fertilizer products (struvite precipitation), or displace biosolids (deep earth digestion) can become more prevalent. Pyrolysis and gasification recover energy in the form of synthetic gas (syngas) and bio-oil by means of thermochemical conversion processes. Yang et al. (2016) showed that a net electricity of 0.071 kWh/m^3 of wastewater treated could be generated from syngas combustion under optimal conditions, and Gikas (2014) estimated that a net electrical energy output of 15.40 MJ/kg dry solids could be generated at a plant with an inlet flow rate of 75,708 m^3/day. In a demonstration project of deep earth (anaerobic) digestion, Geoenvironment Technologies and the City of Los Angeles inject biosolids and RO brine into deep wells (~5000 feet) (Geoenvironment Technologies, 2018). The high temperature anaerobic digestion is expected to generate methane that can be captured as an energy source, but methane production quantities have not been reported.

6. Technology selection and recovery performance

The resource recovery technologies implemented at each scale and the performance of energy and nutrient recovery technologies are summarized in Fig. 6. Recovering energy from wastewater was most prevalent in large-scale plants in the form of biogas and/or electricity generated from sludge. The increase in plant scale results in a higher production of biosolids, which allows for the high capital costs of the energy generation technology to be amortized over a larger volume of biosolids processed. Two energy clusters can be observed in Fig. 6: electricity ranging from 0.14 to 0.97 MJ/m^3, and biogas ranging from 1.3 to 2.9 MJ/m^3. The electricity range was lower because electricity generators have a relatively low conversion efficiency of 33% to 45% (US EIA, 2017).

Clusters for hydropower and thermal energy recovery case studies are also shown in Fig. 6. In the case where 2.5 MJ/m^3 of energy is recovered via hydropower, the plant had a capacity of 22,000 m^3/day and a head loss of 625 m. For another plant with almost half of that capacity and 180 m of head loss, the recovered energy dropped to 0.44 MJ/m^3, which exemplifies the importance of topography. Some studies consider small-scale energy recovery, which results in higher energy recovery intensities (though it should be noted that flow rates are generally much lower). At the large scale, Hao et al. (2015) showed that at least 50% of the total energy consumed by a WWTP (600,000 m^3/day capacity) could be recovered as thermal energy from wastewater, resulting in 17.58 MJ/m^3 of energy recovered using a water source heat pump.

The efficiency of energy recovery varies across scale and technologies. McCarty et al. (2011) reported that the maximum potential energy that can be recovered from the organic content of typical domestic wastewater is about 6.95 MJ/m^3 and the thermal heat available for heat-pump extraction is 25.20 MJ/m^3. However, the latter highly depends on the wastewater's temperature and the ambient temperature. As Fig. 6 shows, recovering energy from the organic content in the form of biogas at the large scale results in a higher efficiency compared to the other energy recovery technologies (up to 43% for biogas vs. 14.4% for electricity and 12% for hydropower). It is also evident that for thermal energy, on-site recovery systems show better performance due to the reduction of heat loss during the wastewater transfer processes (i.e., pumping and conveyance through pipelines).

Nutrient recovery plays a significant role across scales as well. The mass of the nitrogen and phosphorus recovered is shown per cubic meter of the relevant resource (i.e., biosolids, treated wastewater, or urine) in Fig. 6. For context, domestic wastewater contains about 15 g/m^3 of organic nitrogen, 25 g/m^3 of ammonia, and 8 g/m^3 of phosphorus (McCarty et al., 2011). The nutrients recovered from biosolids and from treated wastewater generated two clusters due to the difference in nutrient concentration, which varied by up to two orders of magnitude primarily because of the dewatering of biosolids. Moreover, the highest level of nutrient recovery (and highest efficiency) was achieved at the small scale using urine source separation. Ishii and Boyer (2015) showed that using a urine separation system with a separation efficiency of 80% and struvite precipitation for nutrient recovery, 5.52 kg N/m^3 and 0.447 kg P/m^3 could be recovered in a small-scale system. Considering an average recovery efficiency of 90% for struvite precipitation (Etter et al., 2011) and 80% for urine separation systems, 72% nutrient recovery is achievable is small-scale systems. Nutrient recovery in the form of treated wastewater and biosolids for land application exhibits a significantly lower recovery efficiency across scale (see Fig. 6) due to the dilution of nutrients.

The technologies used for NPR, IPR, and DPR were similar for medium and large scales as exhibited by Fig. 6. This is mainly due to the nature of these technologies, which can be implemented across a wide range of scales and have performance attributes that are acceptable for a variety of reuse purposes (Mutamim et al., 2012; Iorhemen et al., 2016). The technologies used for small scales, however, differ due to specific conditions for treatment that must be accommodated at this scale such as low flow rate, space limitation, and peak flow fluctuation. While biological technologies show relatively low water loss (~5%) during the treatment process (Metcalf & Eddy, 2014), some technologies such as reverse osmosis, nanofiltration, and forward osmosis show higher water rejection for water reclamation (~18%) (Xu et al., 2010) and desalination (~25% to 50%) (Shaffer et al., 2012; Linares et al., 2016). The production efficiency for reclaimed water can also vary based on the system's design characteristics such as the return activated sludge rate, the dewatering process for biosolids management, the number of filtration stages, and the degree of treatment implemented.

The integration of wastewater treatment systems in terms of scale and the type of resource recovered can show significant reductions in costs and environmental impacts (e.g., Chung et al., 2008; Lehtoranta et al., 2014; Kavvada et al., 2016). However, several challenges need to be considered for their implementation, including: monitoring and management; stakeholder cooperation; flowrate reductions to large-scale WWTPs; an increased risk for system failures; availability of licensed operators; social acceptance; and regulatory compliance (Chung et al., 2008; Daigger, 2009; Massoud et al., 2009; Lyu et al., 2016; Maryam & Büyükgüngör, 2017; Khan & Anderson, 2018). Considering the benefits and challenges associated with integrated water and wastewater systems, lack of a comprehensive assessment framework for the design and evaluation of such systems is evident (Byrne et al., 2017; Juan-García et al., 2017). As research and the implementation of integrated systems continues to grow, an in-depth review of their benefits and challenges, holistic sustainability assessments, and the development of suitable decision-making frameworks for their design are recommended for future work.

7. Conclusions

The increasing water demand and the emerging challenges for wastewater treatment plants have motivated the implementation of resource recovery. This study reviewed treatment technologies, water reuse applications, and resources recovered (water, energy, and nutrients) in existing resource recovery cases from the perspective of system scale. A classification of wastewater systems based on scales considering population coverage, treatment technology transition, and existing infrastructure and regulations was also suggested. Non-potable reuse was found to be prevalent across scales, and membrane bioreactors were widely used for NPR applications. IPR and DPR were typically implemented in large-scale systems and relied heavily on membrane filtration such as RO. Energy recovery practices were primarily implemented at the large scale with biogas and electricity as the major forms of energy. In contrast, nutrient recovery had the highest recovery potential in urine at the small scale, but most implementations of nutrient recovery occurred at medium and large scales. The transition away from landfilling and the land application of biosolids to more conservative practices suggests that processes that facilitate waste volume reduction (incineration, pyrolysis/gasification) or displacement (deep earth digestion) could dominate the feasible options in the future. Moreover, struvite precipitation could offer another prevailing means of nutrient recovery since it produces a highly processed fertilizer, which could circumvent the challenges in urban environments where access to farmlands and landfills is limited.

Overall, the outlook is positive for wastewater-based resource recovery systems as the ease of access to water quality monitoring improves to assuage public opposition and concerns about exposure to hazardous constituents, technologies are being developed to overcome challenges such as energy-intensive processes and PPCP removal, and emerging technologies gain trust within communities with the successful implementation of demonstration and full-scale projects.

Declarations of interest

None.

Acknowledgements

This material is based upon work supported by the National Science Foundation Faculty Early Career Development (CAREER) grant of the

United States (No. 1454559). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at https://doi.org/10.1016/j.resconrec.2018.12.035.

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