Two City Pilot Study of Community Non-Potable Reuse Adoption White Paper

Prepared for:

WateReuse Association

Prepared by:

Eastern Research Group, Inc.
110 Hartwell Ave
Lexington, MA 02421

January 31, 2022

ACRONYMS AND ABBREVIATIONS

AC	air conditioner
ACH	air conditioner condensate harvesting
AD	anaerobic digestion
BTU	British thermal unit
CED	cumulative energy demand
CO_2	carbon dioxide
CSO	combined sewer overflow
DDW	displaced drinking water
eGRID	Emissions & Generation Resource Integrated Database
Eq	equivalents
EP	eutrophication potential
EPA	U.S. Environmental Protection Agency
ERG	Eastern Research Group, Inc.
FFD	fossil fuel depletion
FTE	full time employee
GCWW	Greater Cincinnati Water Works
GHG	greenhouse gas
gpcd	gallons per capita per day
gpd	gallons per day
GW MBR	greywater membrane bioreactor
GWP	global warming potential
kWh	kilowatt-hour
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
LM	living machine
MBR	membrane bioreactor
MSDGC	Municipal Sewer District of Greater Cincinnati
NEWR	Non-potable Environmental and economic Water Reuse calculator
NPR	non-potable reuse
NPV	net present value
RW	rainwater
RWH	rainwater harvesting
SFPUC	San Francisco Public Utilities Commission
SFWPS	San Francisco Water Power Sewer Department
TR	thermal recovery
WC	water consumption
WS	water scarcity
WW MBR	mixed wastewater membrane bioreactor

TABLE OF CONTENTS

Page

ABSTRACT

Cities across the U.S. are considering onsite non-potable reuse (NPR) due to its promise as a less environmentally impactful water management strategy and one that can help alleviate water scarcity. However, in locations where water scarcity may not be the primary driver of reuse adoption, onsite NPR may offer other benefits which, to date, are still poorly defined. For example, in addition to reducing potable water consumption, rainwater harvesting systems reduce the amount of stormwater runoff generated by a building, thus providing ancillary stormwater management benefits that could be particularly attractive for combined sewer overflow (CSO) communities. Similarly, onsite wastewater treatment systems such as membrane bioreactors have the potential to reduce organic and nutrient loadings to central sewer systems while also generating a concentrated source of these resources in sequestered sludge, creating the potential for alternative sludge management strategies. The purpose of this study is therefore to provide a more comprehensive accounting of the potential benefits associated with onsite NPR. Using data from two case study buildings and their surrounding CSO sewersheds, we first use EPA's Non-potable Environmental and Economic Water Reuse Calculator (NEWR) to characterize the environmental impacts and economic costs of onsite NPR systems designed for each case study building. We then estimate additional benefits including the effects of onsite NPR systems on stormwater and wastewater generation, both at the building and sewershed scale. Results suggest there are benefits associated with onsite NPR in addition to simply addressing water scarcity concerns that could serve as motivation for more widespread adoption of onsite NPR practices, particularly in less water scarce locations. Specifically, results show:

- Modeled onsite NPR systems in case study buildings could reduce potable water use by 35 and 44%,
- Environmental impacts of modeled systems are generally lower than those of centralized water and wastewater systems,
- Life cycle costs of onsite systems are similar in magnitude to existing water and wastewater service charges,
- RWH systems designed to satisfy onsite non-potable demand can capture nearly all runoff from a building's rainwater collection area, virtually eliminating its contribution to stormwater discharge even during the largest storm events, and
- In most cases, if implemented in just 10% of large buildings in each case study sewershed, reductions in stormwater discharge volumes for large storm events would be of similar magnitude to CSO discharge volumes, suggesting the potential for measurable benefits to CSO communities.

In addition to demonstrating these benefits, this study is intended to provide a screening level framework that can be used by other cities to generate a more comprehensive accounting of the costs and benefits associated with more widespread onsite NPR adoption.

1. INTRODUCTION

In many areas of the U.S., population growth, dwindling water supplies and sustainability concerns are motivating communities to look for alternative sources of water and methods of water treatment. Non-potable reuse (NPR) is one concept that communities are piloting in an effort to improve their water security and sustainability. Onsite NPR, or the installation of treatment systems in individual buildings or districts to collect, treat, and distribute onsite-generated source waters for non-potable uses, is one way communities can increase NPR adoption without investing in complex and costly centralized reuse systems. Still, NPR adoption is not widespread, and requires further study to identify its myriad potential benefits and conditions under which those benefits may be realized.

EPA's Non-potable Environmental and Economic Water Reuse (NEWR) Calculator is a recently developed tool designed to help communities assess the life cycle environmental impacts and costs associated with several onsite NPR treatment systems. NEWR uses basic building characteristics and location (ZIP Code) to estimate how much rainwater (RW), air conditioner (AC) condensate, source separated greywater or mixed wastewater could be generated by the building and its occupants. Then, NEWR compiles life cycle inventories (LCIs)[1] of treatment systems designed to treat each source water to non-potable standards and distribute it back through the building for user-specified non-potable purposes. Based on these LCIs, NEWR calculates a range of life cycle environmental impacts using standard life cycle assessment (LCA) methods and metrics and the life cycle cost of each system.

In addition to potential water savings and environmental impact benefits, onsite NPR has other potential benefits that are not captured by NEWR but may be important to communities and help motivate more widespread adoption of NPR practices. For example, rainwater harvesting (RWH) has the potential to reduce or eliminate stormwater runoff generated by building footprints, providing potential stormwater management cost savings. For buildings that drain to combined sewer systems, these runoff reductions can also contribute to combined sewer overflow (CSO) reductions (De Sousa et al. 2012; Tavakol-Davani et al. 2019). Systems that treat onsite wastewater, such as the membrane bioreactor (MBR) that can be modeled with NEWR, also have the potential to remove a considerable portion of that wastewater, and its pollutants, from a central sewer system. Additionally, most onsite wastewater treatment systems generate a concentrated sludge, which can be collected rather than disposed of in the central sewer system and diverted for beneficial purposes including anaerobic digestion or composting (Hendrickson et al. 2015; Morelli et al. 2019a).

The purpose of this pilot study is to evaluate two case study candidates for onsite NPR, identify benefits beyond water savings that could be realized from onsite NPR adoption, and characterize the conditions under which those benefits could be realized by other buildings in the community. This study is intended to serve as a template that other communities can use to explore the potential benefits of onsite NPR adoption on a community scale. To facilitate other communities performing a similar analysis, a data checklist is included as an appendix to this white paper.

---

[1] Life cycle inventory refers to the data collection and calculation procedures to quantify relevant inputs and outputs of the entire system defined within the system boundaries.

2. METHODS

ERG's analysis consisted of the following steps, which were performed sequentially and follow the layout of the remainder of this white paper:

- *Building Characterization*: Compile characteristics of each case study building, used as input to NEWR models and for calculation of additional benefits.
- *Baseline Model Results*: Run NEWR simulations for each NPR system type using the building characteristics established in the previous section. Use baseline model results of LCA metrics and life cycle cost to inform the design of an optimized system for each case study building, which includes provision of non-potable water from multiple source waters.
- *Optimized Model Results*: Based on preliminary findings, identify the mix of source water types that could maximize study objectives for each case study building, which include:
    - Maximize water reuse
    - Minimize environmental impacts, as measured by NEWR LCA metrics
    - Minimize economic costs
- *Additional Benefits*: Assess additional benefits, including CSO volume and pollutant reduction

ERG performed these analyses using the spreadsheet version of NEWR, which is available in the source documentation of the web application version. The spreadsheet version was used to allow for customization of several key inputs, including per-capita demand and wastewater generation rates, rainfall rates and infrastructure requirements. Each modification made to the underlying model, as well as its justification, is discussed in the applicable section below. Additional discussion of underlying model methods, including a description of the environmental impact metrics, can be found in the Methods and Resources link of the web application of NEWR.

3. BUILDING CHARACTERIZATION

ERG worked with personnel from or familiar with the sewer departments of San Francisco (SFPUC) or Cincinnati (MSDGC) to identify existing or planned buildings that would be suitable candidates for onsite NPR. Once identified, ERG worked with these staff to obtain or estimate building characteristics necessary for input into NEWR (Table 3-1), and for estimation of additional benefits beyond what NEWR can currently model.

The case study system from San Francisco is a planned pair of commercial buildings[2] with a mix of retail and office space. The majority of occupancy is made up of 3,400 full time employees in the office space (FTEs), with the remainder made up of 180 FTEs and 825 transient FTEs in the retail space. Because NEWR does not distinguish between types of occupants beyond the commercial or residential characterization, ERG assumed transient FTEs were equivalent to 0.25 FTEs. Of the 84,886 ft^2 building footprint, 57,853 ft^2 will be a green

---

[2] Although the planned project includes two buildings, ERG treated, and refers to, the project as a single building for ease of calculations and reference. Results are not influenced by this distinction, as any piping necessary to tie both buildings to a common treatment system(s) is likely negligible relative to whole system infrastructure requirements.

roof, 7,722 ft^2 will be irrigated vegetation, and 19,311 ft^2 will be available for rainwater harvesting.

The case study system from Cincinnati is an existing 26-floor building in the downtown area. The first four floors of the building are commercial space, while floors 5-26 contain 231 residential apartment units with an assumed occupancy of 2 people/unit. The Cincinnati building is also located adjacent to a park, with approximately 2.6 acres (114,000 ft^2) of turf that could be used as irrigation demand. Based on current aerial imagery, ERG assumes that the full building footprint is available for rainwater harvesting.

Table 3-1. Case Study Building Characteristics.

Parameter	Units	San Francisco		Cincinnati	
		Value	Note	Value	Note
ZIP Code		94107		45202	
Building Type		Commercial	1	Mixed Use	8
Building Occupants		3786	2	618	9
Number of Floors		9	3	26	10
Building Area	gsf	763,974		390,000	11
Building Footprint	ft^2	84,886	4	15,000	11
Irrigated Area	ft^2	65,575		114,000	12
Irrigated Area – Low Water Use	ft^2	57,853	5	0	
Irrigated Area – Medium Water Use	ft^2	7,722	6	114,000	
Rainwater Catchment Area	ft^2	19,311	7	15,000	

1 – Two office buildings with retail and open space.

2 – 3,400 full time employees (FTEs) in office space, 180 FTEs in retail space, 825 transient FTEs. Assume transient FTEs count as 0.25 FTE.

3 – One building has 8 floors, one has 10, assume average of 9 for calculation purposes.

4 – Building area divided by number of floors.

5 – Total green roof area. Assume low water use.

6 – Total irrigated area less total green roof area.

7 – Total building footprint less total irrigated area.

8 – 231 units w/ 32,000 ft^2 of commercial space.

9 – Assume 2 people per residential unit. Use SF Non-potable Water Calculator for commercial space. Assume space split evenly between general office and general retail, resulting in 118 FTEs and 153 Transients. Assume 1 transient = 0.25 FTE.

10 – 26 story residential (floors 5-26) and commercial (floors 1-4).

11 – Roof area of approximately 15,000 ft^2 based on aerial imagery, assume same for each floor.

12 – Adjacent park (Yeatman's Cove).

4. BASELINE MODEL RESULTS

ERG performed baseline simulations using the building characterization data discussed in Section 3 to characterize potential environmental impacts and economic costs of individual source water types. In addition to the four standard treatment systems, which include a rainwater harvesting system (RWH), air conditioner condensate harvesting (ACH), greywater membrane bioreactor (GW MBR) and a mixed wastewater membrane bioreactor (WW MBR), ERG modeled a combined RWH + ACH system. Because the RWH and ACH systems utilize similar designs and the source waters are of similar quality, a combined system can better utilize the required infrastructure, particularly in climates where RW or AC condensate generation rates may be low. For example, based on extensive testing of NEWR, Arden et al. (2021) showed that RWH and ACH systems that treat larger volumes result in lower environmental impacts and costs per volume of water treated. Both San Francisco and Cincinnati have low RW and AC condensate generation rates relative to other parts of the country, therefore are suitable candidates for a combined system.

4.1 Water Supply and Demand

Based on the inputs in Table 3-1, ERG performed preliminary simulations using NEWR to establish water supply and wastewater generation rates. Default values in NEWR for non-potable demand, greywater generation and mixed wastewater generation were considerably different from those provided by project partners, as shown in Table 4-1. NEWR overpredicted flow rates for San Francisco and underpredicted flow rates for Cincinnati, as data provided by San Francisco were based on more precise water budget calculations and data from Cincinnati were based on existing design code rather than typical use rates. To be conservative in subsequent model simulations, ERG adopted San Francisco's per capita rates for the San Francisco case study commercial building and used NEWR's rates for the Cincinnati apartment building.

Table 4-1. Comparison of City Data Per-Capita Flows to NEWR Default Values.

		San Francisco		Cincinnati	
Flow	**Unit**	**City Data**	**NEWR[1]**	**City Data**	**NEWR[1]**
Non-potable demand	gpcd	3.13	7.6	NA	NA
Greywater generation	gpcd	0.498	4.18	NA	NA
Mixed wastewater generation	gpcd	6.72	11.3	67.2	29

NA: Data not available.

1 – High efficiency demand and generation rates.

ERG also compared NEWR's monthly rainfall for each case study ZIP Code to the most recent 5 years of NOAA daily precipitation[3] data (precipitation data were downloaded for the analysis in Section 6). While NEWR rainfall data for ZIP Code 94107 (San Francisco) were reasonably similar to precipitation rates observed at the San Francisco International Airport[4], NEWR rainfall data for ZIP Code 45202 (Cincinnati) were less than half the observed precipitation rate from the Cincinnati Municipal Airport. This was due to a filter applied to the NEWR precipitation dataset, which removes precipitation from months in which a hard freeze (greater than 4 hours at a temperature less than 28°F) occurs so that only liquid precipitation, or

---

[3] Precipitation is used intentionally throughout this paper to refer to the sum of rain, snow, sleet or hail, all of which are included in NOAA precipitation records. Rainfall, also used throughout this paper, refers specifically to liquid precipitation.

[4] Average annual precipitation from 2016-2020 at the San Francisco International Airport (Station 72494023234) is 16.6 inches. However, this includes a value of 5.4 inches from 2020, which was an anomalously low year. If this year is replaced with 2015 data, for a 5-year span from 2015-2019, the average annual precipitation is 17.4 inches, as 2015 precipitation was only 8.4 inches. NEWR predicts an annual rainfall of 20.2 inches based on a 30-year record.

rainfall, is considered. However, based on daily precipitation and temperature records from 2016-2020, only 3% of Cincinnati's average annual rainfall fell when there was a daily minimum temperature of 28°F or less. ERG therefore used NOAA data for this study, increasing the average annual rainfall for ZIP Code 45202 from 21.6 to 48.6 inches per year based on an average annual precipitation rate of 50.3 inches.

Using revised per capita rates for San Francisco and revised rainfall rates for Cincinnati, ERG performed simulations individually for each of the four source water types available in NEWR. A summary of these source water availabilities is provided in Table 4-2.

Table 4-2. Water Demand and Source Water Generation Rates.

		San Francisco		Cincinnati	
Flow	**Units**	**City Data**	**This Study**	**City Data**	**This Study**
Total Water Demand[1]	gpy	12,322,400	12,322,400	15,154,800	7,594,078
Non-Potable Water Demand[2]	gpy	4,305,467	4,322,584		3,329,081
Rainwater Generation[3]	gpy		182,617		340,643
AC Condensate Generation	gpy		103,273		194,744
Graywater Generation	gpy	687,780	688,181		3,731,731
Mixed Wastewater Generation[1]	gpy	9,285,235	9,286,301	15,154,800	6,546,644
Total Water Demand	gpcd	8.92	8.92	67.2	33.7
Non-Potable Water Demand	gpcd	3.12	3.13		14.8
Rainwater Generation	gpcd		0.13		1.5
AC Condensate Generation	gpcd		0.07		0.9
Graywater Generation	gpcd	0.498	0.50		16.5
Mixed Wastewater Generation	gpcd	6.72	6.72	67.2	29.0

1 – For Cincinnati, city data from Ohio Administrative Code 3745-42-05 (Design flow and waste strength requirements for treatment works sized for one hundred thousand gallons per day or less) 120 gpd/bedroom. For 231 total units, estimate half units 1 bedroom/half 2 bedroom = 346 bedrooms. For pilot study, use NEWR rates, which are more reflective of high-efficiency fixtures.

2 – Toilet/urinal demand + irrigation demand = 3,657,959 + 647,508 = 4,305,467. NEWR non-potable demand adjusted to reflect SF data.

3 – For Cincinnati, NEWR rainfall rates adjusted to reflect data from NOAA station USW00093812, 2016-2020.

Monthly source water generation and non-potable demand rates are illustrated for San Francisco in Figure 4-1 and for Cincinnati in Figure 4-2. For the San Francisco commercial buildings, rainwater, AC condensate and greywater generation rates are very low relative to non-potable demand, while mixed wastewater generation rates are more than double non-potable demand. Rainwater and AC condensate generation rates, although small, show opposite seasonal trends, suggesting a combined system could provide more uniform supply throughout the year than individual systems. Given its intended use as office and retail space, non-potable demand is almost entirely from toilets.

For the Cincinnati apartment building, rainwater and AC condensate generation rates are slightly larger relative to non-potable demand. These source waters are in phase, seasonally, and approximately match the strong seasonal trend in non-potable demand that results from irrigation needs. Greywater generation rates are close to total non-potable demand, while mixed wastewater generation rates exceed non-potable demand during all months.

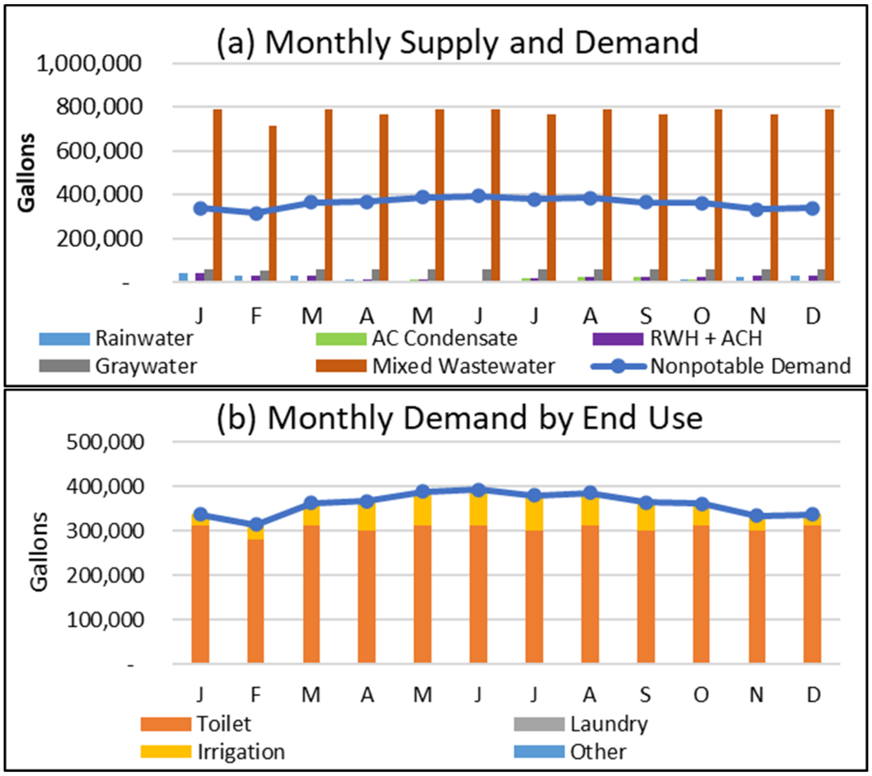

Figure 4-1. San Francisco base model (a) monthly supply and demand by treatment system type and (b) monthly demand by end use.

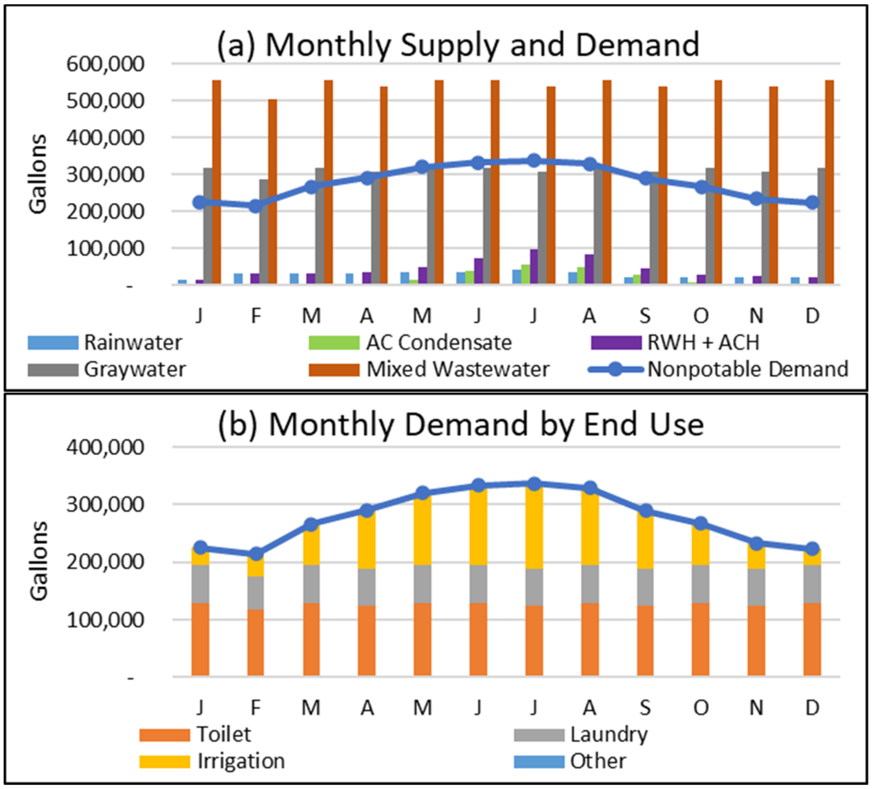

Figure 4-2. Cincinnati base model (a) monthly supply and demand by treatment system type and (b) monthly demand by end use.

4.2 Environmental Impacts and Economic Costs

ERG ran NEWR for each case study system assuming produced non-potable water displaces local drinking water production and distribution. ZIP Code defaults were used within NEWR for characterization of this avoided product. Thermal recovery units for the MBRs were not included in these first model runs so that the performance of just the MBR systems could be evaluated.

Baseline model results for the five NEWR life cycle metrics as well as net present value (NPV) are provided in Table 4-3. As is typical for these system types that are driven by energy consumption, cumulative energy demand (CED) and fossil fuel depletion (FFD) follow similar trends to global warming potential (GWP) (Arden et al. 2021), which is illustrated in Figure 4-3. These results show that the combined RWH+ACH system has the lowest GWP per gallon treated of all treatment options. They also show that displacing drinking water (avoided products) affects results quite differently depending on the location, which is directly related to the electricity grid life cycle greenhouse gas (GHG) emissions' intensity in each location. For example, NEWR uses EPA's Emissions and Generation Resource Integrated Database (eGRID) regional characterization factors for electricity impacts that result in emissions of 0.84 lb CO_2 eq./kWh for San Francisco's region (CAMX region) and 1.5 lb CO_2 eq./kWh for Cincinnati (RFCW region) (U.S. EPA 2018). Figure 4-3 shows that the WW MBR has lower impacts than the GW MBR in San Francisco, but higher impacts than the GW MBR in Cincinnati. The better performance of the WW MBR in San Francisco is due to its size—there are important economies of scale for these systems, and the San Francisco building generates only a small amount of greywater. For the Cincinnati building, which generates a larger volume of greywater, the slightly better performance of the GW MBR is due to its relatively lower electricity use, owing to the lower organics content of greywater compared to mixed wastewater.

Impacts across systems for water consumption (WC) and water scarcity (WS) do not distinguish much between options but do distinguish between cities. Impacts for water consumption show that, due to leakage within the centralized drinking water distribution system, for every 1 gallon of non-potable water provided onsite, approximately 1.1 gallons[5] of raw water is saved in San Francisco and approximately 1.2 gallons[5] of raw water is saved in Cincinnati. Water scarcity results, on the other hand, show greater benefits (results are more negative) to saving raw water in San Francisco, where water is relatively more scarce than in Cincinnati.

System costs, provided in terms of NPV (Fuller and Petersen 1996), represent the life cycle costs of operating each system over a 30-year period using a consistent basis (per gallon of non-potable water provided) and a 5% discount rate. For both locations, the WW MBR produces non-potable water at the lowest cost and ACH at the highest (Table 4-3, Figure 4-4). A large factor in both of these systems is the volume of water treated—highest for the WW MBR, lowest for the ACH system. Combining RW and AC condensate into the same treatment system reduces the NPV of the combined system relative to individual systems, but the RWH+ACH system is still more expensive than either MBR option.

---

[5] Based on personal communication with City partners, leakage rates in city distribution systems are 9.5% in San Francisco, 17% in Cincinnati. NEWR inputs of "Minimum – 10%" and "Default – 18.7%" were therefore used for San Francisco and Cincinnati, respectively.

Table 4-3. Summary of Base Model Results.

System	Volume Treated (gpy)	GWP (lb CO_2 eq/gal)	CED (BTU/gal)	FFD (lb oil eq/gal)	WC (gal/gal)	WS (gal/gal)	NPV ($/1000gal)
Base Model Results, San Francisco							
RWH	182,617	2.78E-3	22.4	8.31E-4	-1.10	-2.03	$82.24
ACH	103,273	3.68E-3	31.0	1.11E-3	-1.10	-2.03	$120.93
RWH+ACH	285,890	2.18E-3	16.5	6.52E-4	-1.10	-2.04	$63.13
GWMBR	688,181	4.74E-3	38.8	1.16E-3	-1.10	-1.93	$43.19
WWMBR	9,286,301	3.96E-3	21.7	7.78E-4	-1.10	-1.93	$6.88
Base Model Results, Cincinnati							
RWH	340,643	-2.4E-04	-0.6	6.9E-05	-1.19	-0.84	$52.58
ACH	194,744	1.9E-05	1.7	1.5E-04	-1.19	-0.84	$64.74
RWH+ACH	535,387	-4.6E-04	-2.7	3.7E-06	-1.19	-0.84	$46.17
GWMBR	3,731,731	2.8E-03	12.7	4.3E-04	-1.19	-0.87	$15.58
WWMBR	6,546,644	4.3E-03	19.0	6.7E-04	-1.19	-0.87	$11.73

GWP = Global Warming Potential, CED = Cumulative Energy Demand, FFD = Fossil Fuel Depletion, WC = Water Consumption, WS = Water Scarcity, NPV = Net Present Value.

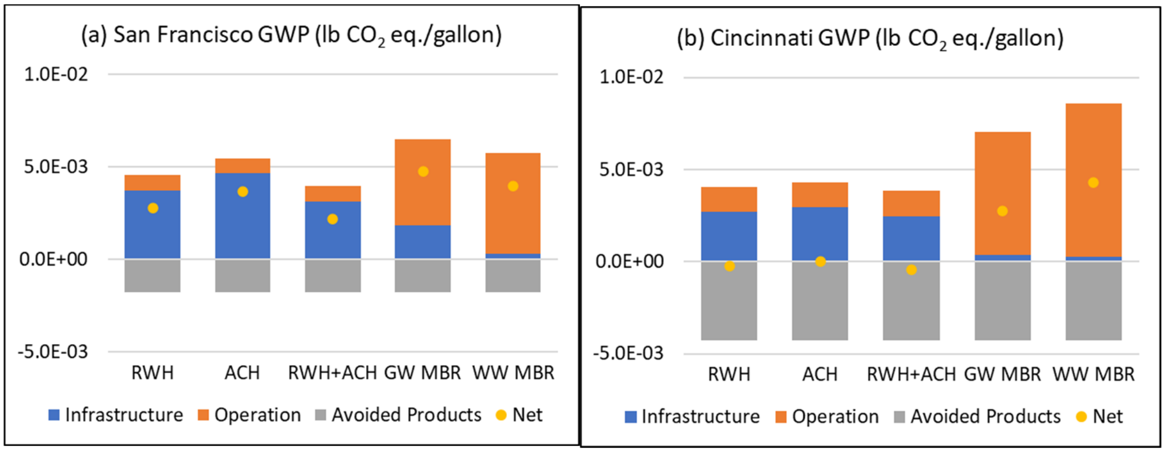

Figure 4-3. GWP of onsite supply options for (a) San Francisco and (b) Cincinnati.

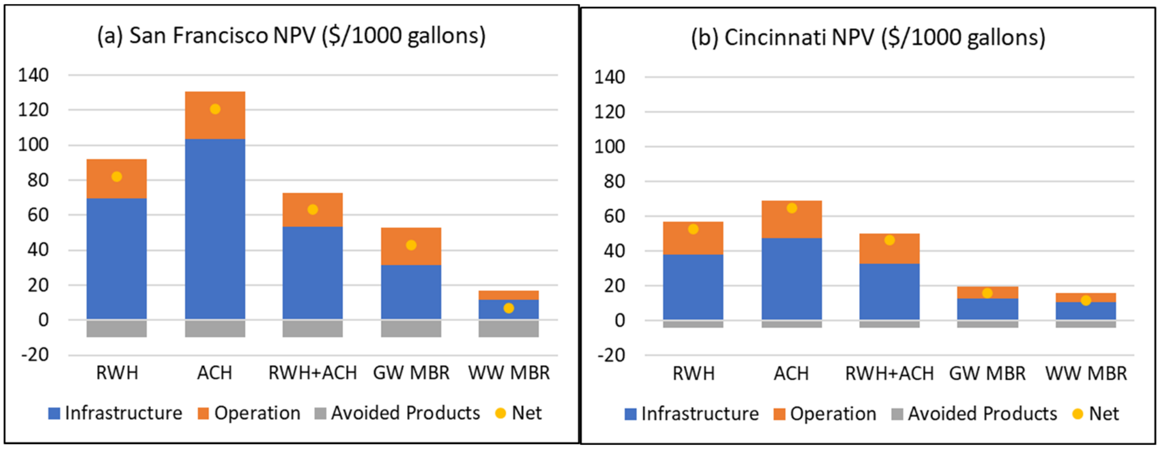

Figure 4-4. NPV of onsite supply options for (a) San Francisco and (b) Cincinnati.

5. OPTIMIZED MODEL RESULTS

Baseline model results presented in the previous section were used to inform the design of an optimized system for each case study location. Because there are many goals of water reuse, including reducing water use, reducing environmental impacts, keeping costs affordable, etc., there is no one best system for any building, and no reason multiple source waters can't be harnessed in the same building to achieve multiple goals. Given the goals of this particular study, which include all of the aforementioned as well as evaluating the effects of onsite reuse on CSOs, the following systems were selected:

- RWH+ACH: Although the combined RWH+ACH system costs more and has higher impacts than MBR systems, its RWH component has the potential to reduce the building's stormwater runoff (discussed further in Section 6), which is a major contributor to combined sewer overflows. Also, because directing RW and AC condensate into the same infrastructure can provide moderate improvements in impacts and costs (Section 4), a RWH+ACH system was selected for each case study system. Tank size, a major determinant of system impacts and costs, was optimized to be as small as possible while still capturing all runoff from the rainwater collection area so as to minimize stormwater discharges (see Section 6).
- WW MBR: Owing to the size advantages of treating what is generally the largest flow of source water in any building, WW MBRs generally have the lowest impacts and costs per volume of non-potable water produced. In addition, mixed wastewater has the highest concentration of onsite-generated pollutants, including organics and nutrients. Therefore, taking even a portion of this flow offline from the central sewer system can reduce a building's contribution to CSO discharges and can create opportunities for alternative sludge management approaches, which are discussed further in Section 6. For this study, a WW MBR was sized to meet the full non-potable demand of each case study system, less what is provided by the RWH+ACH systems. Optimized WW MBRs also include thermal recovery units to provide additional avoided environmental impacts. For the San Francisco system, a thermal recovery unit that offsets electricity was included as natural gas use in new construction is being phased out due to a recently passed ordinance. For the Cincinnati system, a thermal recovery unit that offsets electricity was assumed.

5.1 Water Supply and Demand

Figure 5-1 illustrates the resulting water balance for each case study building using the optimized combination of treatment systems discussed above. The maximum RWH+ACH volume is collected and treated each month, while the remainder of monthly demand is made up with the WW MBR.

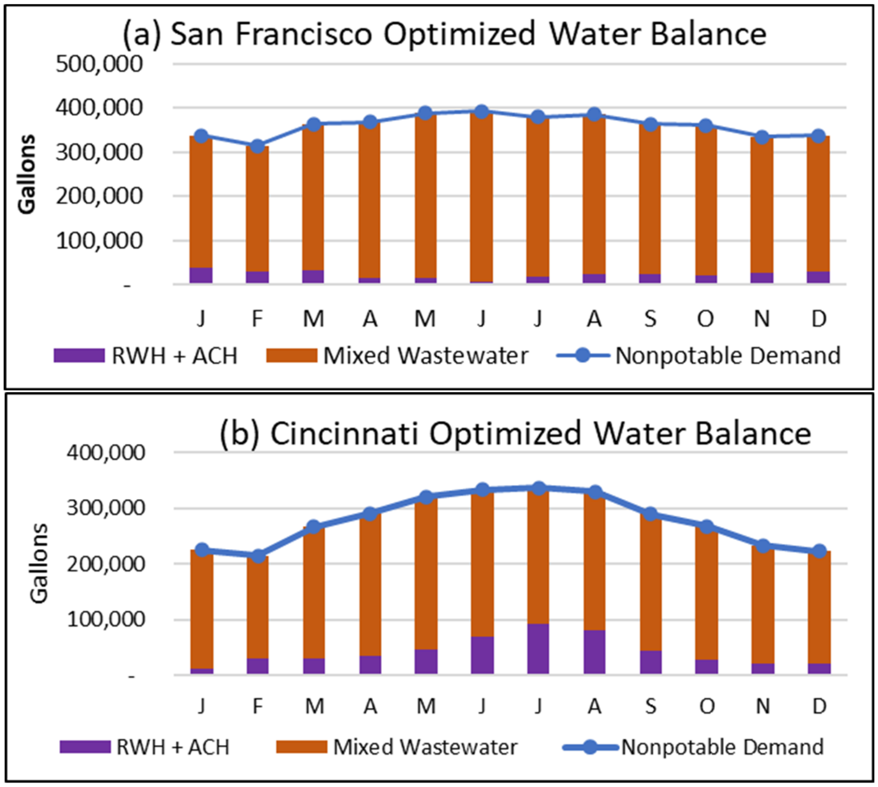

Figure 5-1. Optimized NPR configuration where RWH+ACH is maximized and a mixed wastewater MBR makes up the remaining non-potable demand for (a) San Francisco and (b) Cincinnati.

5.2 Environmental Impacts and Economic Costs

Outputs from each case study NEWR model are provided in Table 5-1. Net impacts and costs include avoided products, which include displaced drinking water and energy offsets from thermal recovery units. Impacts and cost associated with the Cincinnati RWH+ACH system decreased relative to baseline model results, as the default tank size (44,000 gallons) was reduced to 23,000 gallons based on an optimization exercise discussed in Section 6. Results vary for the WW MBRs from the baseline configuration in a few notable ways that are due to the reduced volumes treated and the inclusion of thermal recovery units. WC and WS results are mostly unchanged, with the exception of the San Francisco WW MBR, which sees a 26% decrease in WS impacts. This additional benefit is due to the incorporation of a thermal recovery unit that offsets electricity, which in San Francisco includes a large hydropower component. Although beneficial in many respects, hydropower systems incorporate large reservoirs with considerable surface area and evaporative losses, which are accounted for through the WS metric. GWP and FFD impacts from the RWH+ACH system are higher than the WW MBR but the weighted average, which accounts for the different system sizes, is negative for all impact categories.

Table 5-1. Optimized Environmental Impacts and Economic Costs.

System	Volume Treated (gpy)	GWP (lb CO_2 eq/gal)	CED (BTU/gal)	FFD (lb oil eq/gal)	WC (gal/gal)	WS (gal/gal)	NPV ($/1000gal)
NEWR Optimized Systems, San Francisco							
RWH+ACH	285,890	1.72E-3	11.7	5.07E-4	-1.10	-2.04	$45.08
WW MBR, Elec TR	4,264,198	-6.04E-3	-73.1	-2.73E-3	-1.12	-2.43	$6.35
Weighted Average		-5.56E-3	-67.8	-2.53E-3	-1.12	-2.40	$8.78
NEWR Optimized Systems, Cincinnati							
RWH+ACH	535,387	-1.59E-3	-10.7	-3.43E-4	-1.19	-0.85	$27.32
WW MBR, Elec TR	2,968,909	-1.35E-2	-109	-3.97E-03	-1.20	-0.87	$12.11
Weighted Average		-1.17E-2	-94.3	-3.41E-3	-1.20	-0.87	$14.44

GWP = Global Warming Potential, CED = Cumulative Energy Demand, FFD = Fossil Fuel Depletion, WC = Water Consumption, WS = Water Scarcity, NPV = Net Present Value.

GWP results of the optimized systems are illustrated in Figure 5-2. Results for the San Francisco RWH+ACH system is unchanged from the baseline results (Figure 4-3), however the net GWP of the Cincinnati RWH+ACH system is now negative owing to the more optimized tank size. Net impacts for the WW MBRs are also now less than 0, indicating a net benefit to treatment when thermal recovery is incorporated. Impacts are more negative in Cincinnati, where offsetting electricity is very beneficial owing to the relatively high GHG emissions of the regional electric grid.

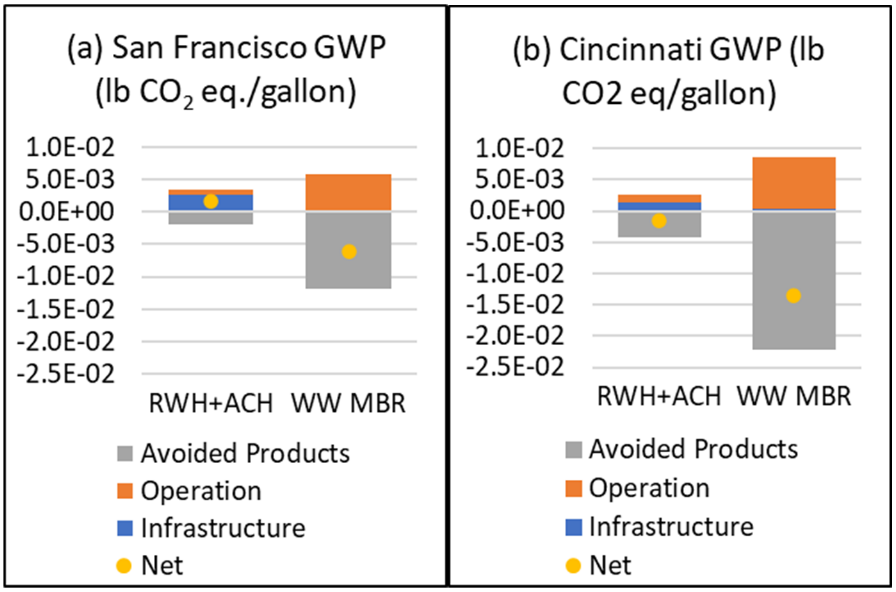

Figure 5-2. Global warming potential of optimized RWH+ACH and WW MBR systems for (a) San Francisco and (b) Cincinnati.

NPV results of the optimized systems are illustrated in Figure 5-3. In both case study locations, the cost of the RWH+ACH system remains relatively high, even with the offset of potable water charges. The cost per volume for the WW MBR is less expensive and more in line with local water rates, especially when the offset of potable water charges is included. Offsetting electricity only has a small effect on NPV, as its cost is low relative to other system costs.

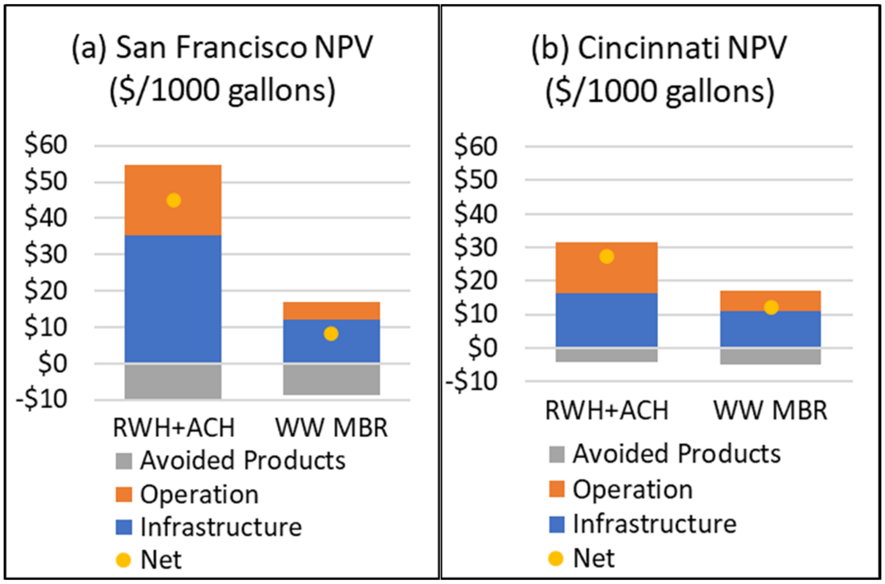

Figure 5-3. Net present value of optimized RWH+ACH and WW MBR systems for (a) San Francisco and (b) Cincinnati.

The results presented in Table 5-1 can also be compared to the results of other LCA studies that have looked at water treatment systems in San Francisco and Cincinnati. Hendrickson et al. (2015) used LCA to calculate GWP requirements of San Francisco's Living Machine (LM), a pilot onsite wetland treatment system that treats office building wastewater for non-potable use. In the study, they also compared the LM to centralized wastewater treatment and evaluated the GWP of hauling sludge generated by the LM to the wastewater treatment plant anaerobic digester. The results of the comparison are illustrated in Figure 5-4.

Although the systems have slightly different boundaries of analysis and background LCA datasets, a couple qualitative points are worth noting. First, the San Francisco WW MBR has a slightly negative GWP, and provides both wastewater treatment and water supply. If compared to the GWP of the centralized WWTP, which only provides one of those two services, impacts of the onsite system are still less. Also, the GWP of LM sludge disposal, which includes extraction pumping energy, transportation distance, and net recovered energy from digesters at the centralized WWTP, is of the same order of magnitude as treatment burdens at San Francisco's WWTP. In other words, if combined with the WW MBR system, this suggests that the GWP of onsite wastewater treatment (WW MBR w/ thermal recovery (TR)) plus sludge hauling and digestion would be comparable in magnitude to existing, centralized wastewater treatment GWP, but have the added benefits of reducing potable demand and reducing wastewater loadings to the central sewer system[6]. Obviously, this takeaway is highly dependent on important site-specific characteristics such as sludge composition and sludge generation rates, but it suggests that the option warrants additional study as additional benefits are possible.

---

[6] NEWR currently assumes that sludge generated by MBRs is discharged to the existing central sewer, with no effect on LCA metrics or cost.

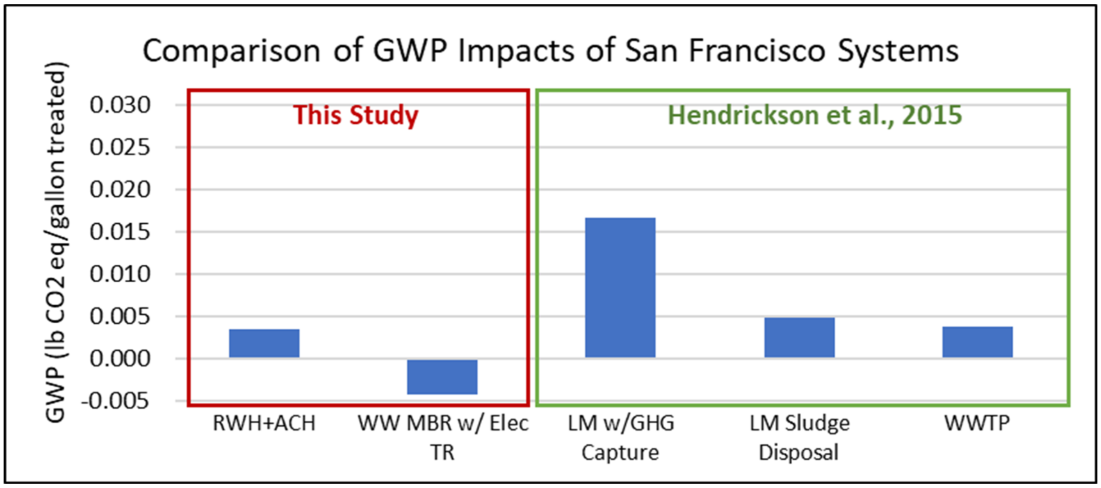

Figure 5-4. Comparison of San Francisco NPR systems (This Study) to systems evaluated by Hendrickson et al. (2015) in terms of global warming potential (GWP). GHG = greenhouse gas, LM = living machine, Elec TR = thermal recovery displacing electricity.

A similarly useful study was performed by Xue et al. (2019) for Cincinnati's centralized drinking water and wastewater systems. Figure 5-5 shows these comparisons for GWP, CED, FFD and WC impacts. Results have all been normalized to the maximum (absolute value) impact for each metric so that results could be presented on a single graph.

Again, we see the RWH+ACH system is generally less impactful than the centralized systems when displaced drinking water is taken into account. Also, the GWP, CED and FFD of displaced drinking water calculated by NEWR underestimates the magnitude of those benefits when compared to the GWP, CED and FFD of centralized drinking water treatment and distribution in Cincinnati. For this study, we used default inputs for NEWR's displaced drinking water module, though users can toggle several inputs to obtain better estimates of the benefits associated with this avoided product. Last, we see that impacts associated with the collection system in Cincinnati are minimal, but impacts at the WWTP itself are on par with drinking water treatment and are greater than impacts associated with the WW MBR. Cincinnati's WWTP does not have an anaerobic digester, therefore would not be suitable for the sludge collection approach evaluated by Hendrickson et al. (2015). However, alternative sludge management strategies or even alternative onsite wastewater treatment systems, such as anaerobic MBRs (e.g., Smith et al. 2014; Morelli et al. 2019) or fertilizer production processes (e.g. Rosato Jr. 2020) could be considered.

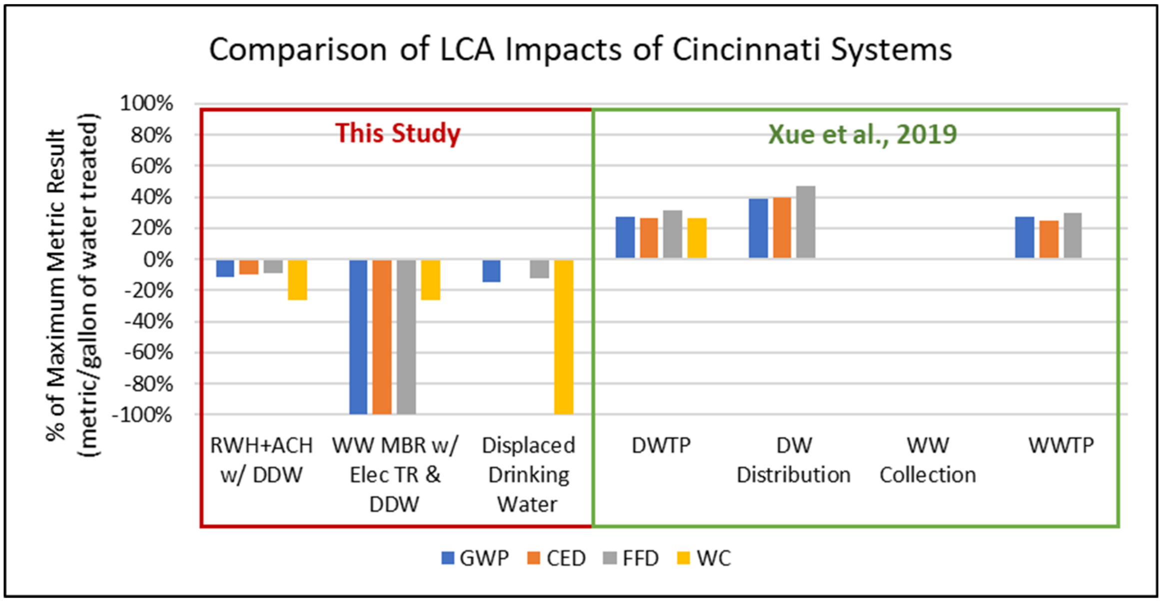

Figure 5-5. Comparison of Cincinnati NPR systems (This Study) to Cincinnati centralized drinking water (DW) and wastewater (WW) systems evaluated by Xue et al. (2019) in terms of global warming potential (GWP), cumulative energy demand (CED), fossil fuel depletion (FFD) and water consumption (WC). DDW = displaced drinking water.

5.3 Economic Analysis

In order to more fully evaluate the economic implications of onsite NPR adoption, ERG performed a pre/post analysis of annual expenditures of each case study building for water service provision, including water supply (potable and non-potable), wastewater treatment and stormwater management (for Cincinnati only). ERG obtained rate schedules for each location to estimate costs under existing conditions (i.e., no onsite NPR). Due to the difficulty of estimating the size and number of meters in each building, ERG did not include flat base charges and only included the first, and highest, rate in each rate schedule. ERG then used NPV estimates from NEWR to estimate similar costs under the onsite NPR implementation scenario.

Stormwater charges were not included for San Francisco as building owners are only charged for stormwater management if they do not have a water or wastewater account with SFPUC. Stormwater charges for the Cincinnati building were obtained from Cincinnati’s Stormwater Management Utility. Stormwater rates for the existing scenario, which are based on the area of impervious surface, were only applied to the rooftop area that contributes to the RWH system under the NPR scenario—stormwater from other impervious surfaces, such as sidewalks and driveways, remains unchanged between pre/post scenarios.

Annual charges for the onsite NPR implementation scenario include costs associated with onsite treatment systems, including thermal recovery units for WW MBRs, but no costs associated with displaced drinking water. A summary of the annual charges are provided in Table 5-2. Estimated costs associated with water provision are higher in San Francisco than Cincinnati, leading to an annual service charge of $344,795 per year for the San Francisco case study building compared to $82,628 for the Cincinnati case study building. Potable water charges for San Francisco ($173,799 per year) are roughly similar to wastewater charges, which include a volume, COD and TSS ($170,997 total). For Cincinnati, wastewater charges

($51,454/year) are greater than water charges ($30,458), and stormwater costs are minimal ($716/year).

For the onsite NPR scenario, the cost per 1000 gallons of the RWH+ACH system is the highest of all line item charges. However, it only provides a fraction of non-potable demand, and the weighted average cost of onsite NPR is $19.41/1000 gallons and $18.63/1000 gallons for San Francisco and Cincinnati, respectively. Although these are larger costs than individual water or wastewater rates, they are providing both services simultaneously, so should be compared to the sum of existing water, wastewater and stormwater charges. For San Francisco, onsite NPR is less expensive than existing water and sewer rates, leading to a decrease in annual charges. For Cincinnati, given the low existing rates, onside NPR is more expensive, but not considerably. Importantly, inclusion of a RWH+ACH system can also address CSOs, the costs of which are not included in this analysis.

Table 5-2. Economic Analysis Results Comparing Annual Water, Wastewater, and Stormwater Service Charges With and Without Onsite NPR.

Parameter	San Francisco					Cincinnati				
	gpy	$/1000gal	ft^2	$/ ft^2/yr	$/yr	gpy	$/1000gal	ft^2	$/ ft^2/yr	$/yr
Existing										
Drinking water[1,2]	12,322,400	$14.10			$173,799	7,594,078	$4.01			$30,458
Wastewater (volume)[1,2]	9,286,301	$12.65			$117,444	6,546,644	$7.86			$51,454
Wastewater (COD)[1]	9,286,301	$2.74			$25,472					
Wastewater (TSS)[1]	9,286,301	$3.02			$28,081					
Stormwater[3,4]								15,000	$0.05	$716
Total Cost to Building					**$344,795**					**$82,628**
Onsite NPR Implementation										
Potable water use	7,999,816	$14.10			$109,623	4,089,783	$4.01			$16,403
Untreated wastewater (volume)	5,022,102	$12.65			$63,515	3,577,735	$7.86			$28,120
Untreated wastewater (COD)	5,022,102	$2.74			$13,775					
Untreated wastewater (TSS)	5,022,102	$3.02			$15,186					
RWH + ACH NPV[5]	285,890	$54.86			$15,685	535,387	$31.46			$16,845
WW MBR NPV[5]	4,264,198	$17.03			$72,615	2,968,909	$16.31			$48,433
Total Cost to Building					**$293,607**					**$109,800**

General Note: Rates used here are based on the first (highest) rate in each rate schedule and do not include monthly base charges.

1 – San Francisco rates obtained from San Francisco Rates Schedules and Fees. Assumes wastewater has a COD concentration of 508 mg/L and TSS of 220 mg/L after Morelli et al., (2019a). Assumes oil and grease is negligible.

2 – Cincinnati drinking water rates obtained from GCWW Residential Rate Brochure, wastewater rates from 2021 Sewer Rate Information

3 – Stormwater costs for San Francisco from ARUP, 2016

4 – Stormwater costs for Cincinnati from Cincinnati's Stormwater Management Utility's rate structure for the contribution from the 15,000 ft^2 contributing area and assuming Commercial Intensity Development Factor.

5 – NPV of onsite NPR systems only includes the cost of onsite treatment and non-potable water provision. WW MBR systems include the cost of thermal recovery units. No displaced drinking water costs are included.

6. ADDITIONAL BENEFITS

6.1 CSO Volume Reduction

As part of this project, ERG has worked with partners at the SFPUC and U.S. EPA to identify small CSO sewersheds that would be suitable candidates for onsite reuse, and with sufficient data to estimate the benefits to CSO impacts of community adoption of onsite reuse practices (Table 6-1). For San Francisco, the SFPUC identified three outfalls with annual overflows of less than 1 million gallons (MG), including Mariposa St, 20th St, and Evans St outfalls. SFPUC's sewersheds, illustrated in Figure 6-1[7], are located in urbanized areas, have a total contributing area of approximately 700 acres and discharge a total of 0.9 MG of combined sewage in a typical year (SFPUC 2021). For Cincinnati, three outfalls were also identified, with two having total annual overflow volumes that are on average less than 1 MG, and one outfall having a much larger annual overflow volume of 13.3 MG. In contrast to the San Francisco outfalls, those from Cincinnati discharge more frequently, with an average annual number of events of 8.3 compared to 2 for San Francisco.

Table 6-1. Characteristics of Study CSO Sewersheds

CSO Sewershed	Area (acres)	Typical # of Events per Year	Average Annual Total Overflow Volume (MG)
San Francisco			
Mariposa	199	3	0.7
20th Street	37	2	0.1
Evans Street	484	1	0.1
	Average:	2.0	
Cincinnati			
CSO 54	58	8.6	0.12
CSO 468	346	9.8	13.3
CSO 560	681	6.6	0.36
	Average:	8.3	

San Francisco Data Sources: Drainage areas from SFPUC. Overflow attributes from SFWPS 2021.
Cincinnati Data Sources: Drainage areas and overflow attributes from B. Smith (personal communication, January 2022).

---

[7] Due to security concerns, Cincinnati sewershed locations are not illustrated.

Figure 6-1. Small CSO sewersheds with <1 MG of annual overflow volume (SFPUC 2021).

San Francisco also performed an evaluation of the potential for onsite NPR systems to reduce CSO overflows. Using the three sewersheds from Table 6-1, SFPUC modeled the combined sewer systems during typical storm events and reduced wastewater flow by 10-25% (simulating implementation of onsite wastewater reuse systems) to determine if reductions in CSO volume would result. Results of the analysis indicated that even if 25% of wastewater was removed from the system, insignificant reductions in CSO volumes would occur[8]. In follow-up discussions, SFPUC staff indicated that wastewater often makes up 1% or less of overflow volumes, thus the results were to be expected (A. Chastain, personal communication, October 2020).

Conversely, the majority of overflow volume is composed of stormwater. We therefore look next at the potential effects RWH systems may have on stormwater volume reductions during large, overflow-causing storm events.

6.1.1 Stormwater Reduction Benefits

Because CSOs are wet weather events, ERG performed a daily water balance analysis for each case study system to estimate the volume of collected rainwater in a typical year that,

---

[8] Although minor reductions were modeled, they were deemed insignificant as they were less than the range of uncertainty of model predictions.

absent a RWH system, would otherwise be considered stormwater runoff and contribute to CSOs. The analysis assumes that existing overflow volumes are due to the runoff generating potential of the existing land cover, and that any changes to that runoff generating potential would have a direct influence on total stormwater runoff volume. In other words, the analysis estimates the benefit of collecting rainwater on any currently untreated impervious surface. The analysis is normalized to rainwater collection area, as opposed to total building area or parcel size, so that results can be extrapolated to other buildings within the sewershed that may be considering RWH for NPR.

To perform the analysis, ERG used the most recent 5 years of daily precipitation and temperature data from the San Francisco International Airport (NOAA Station 72494023234) and Cincinnati Municipal Airport (NOAA Station USW00093812). Temperature data were used to filter out non-liquid precipitation events, which was only applicable to Cincinnati[9]. ERG then calculated daily runoff volumes generated from each building's rainwater collection footprint under existing conditions using the Natural Resource Conservation Service (NRCS) Runoff Curve Number method (Cronshey 1986). For the San Francisco case study building, the current land cover is unknown, therefore ERG estimated a low and a high runoff potential across a plausible range of typical, untreated urban land covers. Low runoff land uses were assumed to have an RCN of 80, which is representative of high runoff residential areas or low runoff commercial/industrial area. High runoff land uses were assumed to have an RCN of 98 and be representative of impervious areas. For the Cincinnati case study building, although the current building appears 100% impervious from aerial imagery, ERG applied the same high/low approach to estimate a range of runoff reductions that may be more broadly applicable to other buildings.

Next, ERG filtered daily runoff results down to only those events likely to cause overflows. For example, although the model estimates an average of 0.048-0.311 MG of runoff per year could be generated from the Cincinnati building's 15,000 ft^2 rainwater collection area, much of that runoff volume would likely occur during storm events not large enough to trigger an overflow. Although this threshold—the size of storm likely to cause an overflow—is highly variable, we used overflow frequency data from Table 6-1 to come up with an approximation for each city. Those data suggest that across the three San Francisco sewersheds, overflows occur 1-3 (average 2.0) times per year[10]. Across the three Cincinnati sewersheds, overflows occur 6-10 times per year (average 8.3). ERG therefore toggled the rainfall threshold criteria until the number of annual exceeding events from each location's 5-year daily rainfall record matched the average number of overflow events. ERG then summarized the range of annual runoff volumes that would be expected from storm events larger than that threshold. Table 6-2 summarizes those results. A threshold of 1.1 inch/day for San Francisco and 1.2 inch per day for Cincinnati results in an average annual number of qualifying storm events of 2.0 and 8.2, respectively.

---

[9] Following a similar filtering approach used by NEWR, precipitation events that occurred on days with a minimum temperature of 28°F or less were assumed to be snow or sleet and not able to produce runoff.

[10] Other sewersheds have up to 12 overflows in a given year. We limit this analysis to only three sewersheds both to be conservative and to demonstrate the method.

Table 6-2. Rainfall Characteristics and Annual Runoff Volumes from Large Daily Events Over a Five-Year Period.

Year	Total Rainfall (in)	Days Exceeding Rainfall Threshold	Event Size Range (in/day)	Existing Runoff, Low (gpy)	Existing Runoff, High (gpy)	Runoff per Area, Low (g/ft²/yr)	Runoff per Area, High (g/ft²/yr)
San Francisco, 19,311 ft² RW collection area, threshold 1.1 inch/day							
2015	8.44	1	1.21	1,890	11,982	0.10	0.62
2016	20.03	2	1.32-1.44	5,530	27,978	0.29	1.45
2017	22.75	5	1.18-1.86	18,341	78,038	0.95	4.04
2018	14.26	1	2.94	14,507	32,603	0.75	1.69
2019	20.72	1	1.49	3,380	15,291	0.18	0.79
Average	**17.24**	**2**	**1.71**	**8,730**	**33,178**	**0.45**	**1.72**
Cincinnati, 15,000 ft² RW collection area, threshold 1.2 inch/day							
2016	42.52	7	1.53-3.47	33,844	106,887	2.26	7.13
2017	44.86	6	1.42-2.31	27,406	91,427	1.83	6.10
2018	56.09	11	1.25-3.41	62,188	181,233	4.15	12.08
2019	50.51	7	1.25-3.2	29,932	100,325	2.00	6.69
2020	49	10	1.29-2.5	40,457	142,657	2.70	9.51
Average	**48.596**	**8.2**	**1.84**	**38,765**	**124,506**	**2.58**	**8.30**

Next, ERG modeled rainwater collection and tank overflows (i.e., runoff) under proposed conditions where a combined RWH+ACH system is installed in each building to collect rainwater from the area designated for collection (Table 3-1). The following equation describes the daily water balance used to calculate the available storage capacity of the tank:

Equation 1. $V_{end\ of\ day} = RW_d + AC_d - NP\ Demand_d - Overflow_d$

Where,

$V_{end\ of\ day}$ = the volume of water remaining in the tank at the end of the day (gallons)
RW_d = daily RW volume collected (gallons)
AC_d = daily AC condensate volume generated (gallons)
$NP\ Demand_d$ = daily non-potable demand (gallons)
$Overflow_d$ = daily overflow volume if inputs (RW_d and AC_d) minus outputs ($NP\ Demand_d$) exceed the space available from the previous day (gallons)

Assumptions include:

- To be conservative in the amount of space available in the tank each day, RW_d was calculated by only abstracting an initial interception of 0.2 mm from each daily rainfall depth (Rammal and Berthier 2020), instead of using NEWR's default 75% collection efficiency
- AC_d is the daily conversion of monthly generation rates calculated by NEWR
- $NP\ Demand_d$ is the daily conversion of monthly demands calculated by NEWR and does not take into account weekday/weekend demand differences
- Building non-potable use prioritizes emptying the RWH+ACH tank before using non-potable water produced by the WW MBR

To estimate the tank size required to eliminate tank overflows, or runoff generation, ERG first ran the model with default tank sizes predicted by NEWR. For San Francisco, the default tank size of 23,824 gallons proved to be adequate to treat all but a negligible 127 gallons per year that resulted from a single daily rainfall of 2.94 inches in 2018, suggesting that a RWH+ACH system with a tank size of 1.24 gallons/ft^2 of collection area could nearly eliminate runoff generation from that collection area. For Cincinnati, the default tank size of 44,616 gallons proved larger than needed. A smaller tank size of 23,000 gallons, or 1.53 gallons/ft^2 of collection area, proved adequate to capture all rainwater over the 5-year period and not affect RWH+ACH supply volumes.

Based on the above estimate of existing conditions runoff volumes combined with optimized tank sizes that eliminate runoff over a 5-year period, these results suggest that the case study RWH+ACH systems could provide stormwater volume reductions during large storm events of 0.009-0.033 MG/year in San Francisco, and 0.039-0.125 MG/year in Cincinnati. Based on the data provided by SFPUC (Table 6-1), if the San Francisco building was located in either sewershed with an annual overflow volume of 0.1 MG/year, its volume reduction potential would represent 9-33% of the annual overflow volume. If located in the Mariposa sewershed, its contribution would be less, but still meaningful at 1.2-4.7% of annual overflow. Similarly, if the Cincinnati building were located in any of the sewersheds from Table 6-1, its contribution to annual stormwater volume reduction would range from 0.3-103% of average annual overflow volumes.

The results above show that the magnitude of stormwater volume reductions provided by RWH systems is potentially large enough to have a measurable effect on annual overflow volumes. Next, we estimate similar stormwater reductions for scenarios where RWH systems are adopted at multiple buildings within each sewershed.

6.1.2 Community Benefits

Using the area-normalized results of Table 6-2, we can extrapolate stormwater volume reduction benefits to other buildings and CSO sewersheds within each community. This extrapolation should be realistic, however, and targeted to larger buildings that are more likely to have the funding for installation of a RWH or RWH+ACH system and are more likely to need systems that are large enough to realize the environmental and economic performance benefits discussed in Section 5. For example, past research indicates that the onsite NPR systems evaluated by NEWR have strong economies of scale and perform poorly at smaller sizes (Arden et al. 2021). Because the relationship between size and environmental or economic performance is highly dependent on location, we first modeled a RWH+ACH system across a range of building sizes (roof areas) in each City to evaluate economies of scale. These results, in terms of GWP and NPV as proxies for environmental and economic performance, respectively, are illustrated in Figure 6-2.

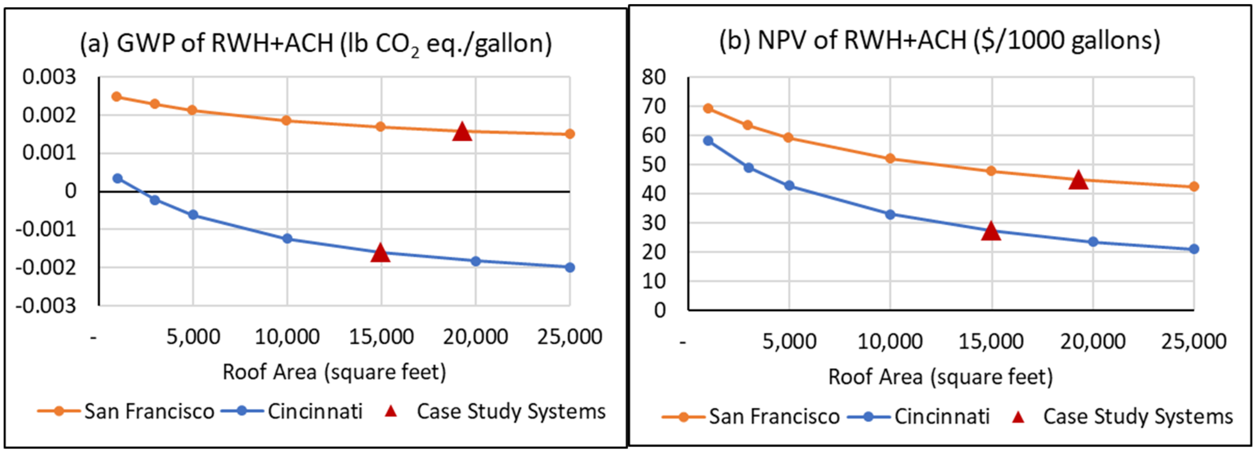

Figure 6-2. Global warming potential (GWP, tile (a)) and net present value (NPV, tile (b)) for a RWH+ACH system modeled across a range of roof areas for each case study city. Model results assume that non-potable demand does not limit the capacity of the RWH+ACH system.

Although there is no criteria for what constitutes “good” vs “bad” environmental or economic performance of onsite NPR systems, we can see from Figure 6-2 that as the size of the RWH+ACH systems decreases, GWP and NPV increase non-linearly. For the purpose of this analysis, we chose 5,000 ft^2 as a threshold, below which we assume the cost or environmental performance of these systems would be too poor to justify their installation.

Using this roof area threshold of 5,000 ft^2, we identified the number of buildings larger than 5,000 ft^2 in each sewershed from Table 6-1 as well as their cumulative roof area, using building footprint data obtained from each city’s GIS department (DataSF 2020; CAGIS 2021). We then assume that 10%[11] of those buildings would be suitable candidates to installation of a RWH or RWH+ACH system, and that 75%[11] of each candidate’s roof area would be suitable for rainwater collection. Last, using the values from Table 6-2 for runoff reduction per roof area, we obtain an estimate for the range of stormwater volume reduction that could be achievable for overflow-causing storm events across each sewershed. Results are presented in Table 6-3.

---

[11] These values are only reasonable estimates intended to illustrate a possible scenario, and other values could be used by other communities.

Table 6-3. Estimated Stormwater Volume Reductions from 10% RWH Adoption Across Case Study CSO Sewersheds.

CSO Sewershed	Area (acres)	# of Rooftops > 5,000 ft²	Total Area of Rooftops > 5,000 ft²	Average Annual Overflow Volume (MG)	Estimated Stormwater Volume Reduction (MG)[1]
San Francisco					
Mariposa	199	97	1,491,720	0.7	0.05-0.19
20th Street	37	15	359,633	0.1	0.01-0.05
Evans Street	484	96	1,518,134	0.1	0.05-0.2
Cincinnati					
CSO 54	58	14	97,335	0.12	0.02-0.06
CSO 468	346	18	283,820	13.3	0.06-0.18
CSO 560	681	80	951,943	0.36	0.18-0.59

1 – Estimated assuming 10% of the buildings > 5,000 ft² would be suitable candidates, and 75% of their roof area would be suitable for rainwater collection.

The results in Table 6-3 show that the range of potential stormwater volume reductions that could be achieved during large storm events in the case study sewersheds is of a similar magnitude as the annual overflow volumes, with the one exception of CSO 468 in Cincinnati.

6.1.3 Limitations

The stormwater volume reduction method described in Sections 6.1.1 and 6.1.2 is intended to provide an order of magnitude estimate of the potential for RWH systems to provide additional benefits to CSO systems. It is based on daily rainfall totals and does not account for complex hydraulics within a sewershed, which are ultimately what drive CSO characteristics. Stormwater volume reduction estimates should not be interpreted as being equivalent to CSO volume reductions. Rather, they should be interpreted as an indication of the potential for additional benefits.

6.2 Pollutant Reduction

The mixed wastewater MBR treatment systems offer several potential benefits to wastewater-based pollution reduction. First, by treating wastewater for subsequent non-potable uses, they can abstract a considerable portion of wastewater volume from an existing sewer system, reducing the burden on existing centralized collection and treatment facilities. Second, they concentrate pollutants in sludge, which opens up the potential for alternative management strategies. For example, if the centralized wastewater treatment plant has an anaerobic digester, sludge can be periodically hauled to the digester, circumventing centralized collection facilities and the majority of the centralized wastewater treatment process (Hendrickson et al. 2015). This approach may also be suitable for communities pursuing a food waste collection and co-digestion program (e.g., Morelli et al. 2019b; Morelli et al. 2020). Sludge can also be processed into high quality fertilizers (e.g., Rosato Jr. 2020). Alternatively, onsite systems can be optimized for nitrogen removal through incorporation of anaerobic processes (Yoon 2016).

For the case study systems, ERG estimated mass flows of total suspended solids (TSS, used as a surrogate for total solids), volatile suspended solids (VSS), total nitrogen (TN) and total phosphorus (TP) generated onsite and routed through the WW MBRs (Table 6-4). WW MBR mass balances are based on original GPS-X models used to design and parameterize the treatment systems (Morelli et al. 2019a).

Table 6-4 shows that WW MBRs treat 46% (San Francisco) and 45% (Cincinnati) of generated wastewater in the case study buildings. Of that treated wastewater, 70% of VSS, 34% of TN and 50% of TP are sequestered in sludge and could be managed through alternative approaches discussed above. The fraction of treated solids and nutrients not sequestered in sludge are either removed through treatment processes (e.g., VSS and TN reduction in the MBR itself) or removed from the reuse cycle through irrigation loss pathways. Based on GPS-X model results, NEWR WW MBRs generate 0.00142 lb of sludge for every gallon of wastewater treated. For the San Francisco and Cincinnati systems, this translates to 17 and 12 lb/day or 500 and 350 lb/month, respectively.

Table 6-4. Solids and Nutrient Mass Balance for Case Study WW MBRs.

Flow	WW Flow (gpd)	Solids (lb/d)	VSS (lb/d)	TN (lb/d)	TP (lb/d)
San Francisco					
Generated	25,439	46.7	37.4	7.4	1.2
Treated	11,683	21.4	17.2	3.4	0.5
Sequestered in Sludge	167	16.8	12.0	1.1	0.28
Cincinnati					
Generated	17,936	32.9	26.3	5.2	0.8
Treated	8,134	14.9	11.9	2.4	0.4
Sequestered in Sludge	116	11.7	8.4	0.80	0.19

Water quality data source: GPS-X model results from Morelli et al. 2019a.

Assuming an alternative sludge management pathway is utilized and the entire 45-46% of wastewater is diverted from the central sewer system, ERG estimated the mass implications of this reduction relative to the total mass of nutrients within typical CSO sewersheds for which dry weather flow estimates were available. Using dry weather flow estimates from SFPUC (2021) and B. Smith (personal communication, January 2022) and water quality data from the Bay Area Clean Water Agencies Group Annual Report (BACWA 2021)[12], ERG estimated the total daily mass of nutrients conveyed within each CSO sewershed during dry times. Combined with the data in Table 6-4, results suggest that if the San Francisco building were located in the Mariposa sewershed, nutrients associated with the wastewater treated by the WW MBR would represent between 0.9 and 1.2% of TN and TP loadings. However, the dry weather flow rate of the Mariposa Pump Station is considerably higher than those from CSO 54 and 468 sewersheds in Cincinnati. By comparison, if the Cincinnati case study system were located in the CSO 54 sewershed, nutrients associated with the wastewater treated by the WW MBR would represent between 6 and 9% of TN and TP loadings. In terms of nutrients sequestered in sludge, the WW MBR would sequester 3-6% of dry weather flow nutrients.

---

[12] Water quality data were not available for dry weather flow from Cincinnati.

Table 6-5. Summary of Dry Weather Nutrient Loadings in Case Study CSO Sewersheds.

Sewershed	Dry Weather Flow (MGD)	TN (mg/L)	TP (mg/L)	TN (lb/d)	TP (lb/d)
San Francisco					
Mariposa Pump Station	1.00	46	5.6	383	47
Cincinnati					
CSO 54	0.096	46	5.6	37	4
CSO 468	0.18	46	5.6	69	8

Sources: San Francisco sewershed characterization data from SFWPS (2021). Water quality data from BACWA (2021). Cincinnati sewershed characterization data from B. Smith (personal communication, January 2022). No dry weather flow water quality data for Cincinnati available so assume similar to San Francisco.

6.2.1 Community Benefits

The analyses performed above, particularly that performed by SFWPS (2021), suggested negligible CSO benefits associated with the removal of wastewater from a combined sewer system. However, as shown in Section 6.2, the quantity of nutrients that can be sequestered in the sludge of a WW MBR may not be negligible, particularly if the system is located in a sewershed with a relatively low dry weather flow rate. Scaling up of the nutrient sequestration results described in Section 6.2 would require, at the very least, characterization of sewershed building occupancies, which is beyond the scope of this study. Still, Section 5 demonstrated that environmental and economic benefits to onsite NPR systems could be possible when only considering the offset of water supply; consideration of additional benefits, such as sequestration of nutrients in sludge, could be advantageous for some communities under the right circumstances. For example, onsite wastewater treatment systems for NPR could offset pressure to expand central water and wastewater treatment plants due to urban growth. In these cases, costs and environmental impacts of alternative sludge collection approaches should be considered comprehensively alongside the range of costs and benefits discussed in this study.

6.2.2 Limitations

The estimate of potential nutrient reduction benefits performed above is based on average observed nutrient concentrations at San Francisco's wastewater treatment plant. Concentrations within portions of the sewer system could vary from these averages, both in time (season) and space. Additionally, extrapolation of these results to reductions in CSO nutrient loadings may be difficult as an analysis of dry weather loading does not take into account nutrient loading from stormwater, which can be highly variable. Differences in usage characteristics between different building types (e.g., office vs. residential) are also likely to influence nutrient loadings and the potential for nutrient sequestration.

7. CONCLUSIONS

The results of this pilot study have demonstrated that the benefits of onsite NPR can be numerous, especially when large buildings adopt a diversified approach. Specifically, this analysis shows:

- Onsite NPR systems can reduce the potable demand of the case study systems by 35 and 44%. Based on typical centralized distribution system leakage rates and including life cycle water consumption rates of the onsite NPR systems, this translates to a life cycle water consumption reduction of 40% and 53%.
- A dual RWH+ACH and WW MBR system installed in each case study building can lead to net negative environmental impacts (i.e., benefits) in terms of GWP, CED, FFD, WC and WS. Compared to existing centralized water and wastewater treatment, which both have net positive impacts in these categories, onsite NPR represents a net reduction in these impact categories.
- A dual RWH+ACH and WW MBR system installed in each case study building would likely have comparable life cycle costs to existing water, wastewater and stormwater expenses. Net increases or decreases in cost depend most on how expensive existing rates are, and the size of the NPR systems (which depend on non-potable demand) as there are important economies of scale at the building level.
- A RWH+ACH system in either building has a storage tank size that is large enough to capture all of the potential stormwater runoff from its rainwater collection area, suggesting that a rainwater collection area's contribution to CSOs can be eliminated by installing a RWH system. In both case study locations, RWH+ACH treatment volume is limited by rainfall and AC condensate availability, not non-potable demand, therefore results can be reasonably extrapolated to other buildings in these communities using an area-normalized metric.
- Using the proposed extrapolation approach, results suggest that adoption of RWH systems in just 10% of buildings with roof areas greater than 5,000 ft^2 in each case study sewershed could result in reductions in the volume of stormwater generated during CSO events that is of similar magnitude to total overflow volumes.
- In both case study buildings, which include a commercial and a mostly residential building, a WW MBR has the potential to treat approximately 45% of onsite generated wastewater. If alternative sludge management strategies are adopted (NEWR currently assumes sludge is discharged to the existing central sewer), this total volume, and the pollutants it carries, can be diverted from a collection system and its contribution removed from CSO discharges. Moreover, the sludge that is produced represents a concentrated stream of volatile solids and nutrients, which could be diverted to an anaerobic digester, reduce treatment burdens at the rest of the wastewater treatment plant, and be beneficially converted to energy and or fertilizer substitutes such as struvite or compost. Based on the findings of this study, these alternative sludge management pathways could be environmentally beneficial and warrant further study.

To facilitate other communities performing a similar analysis as the one presented here, a data checklist is included as an appendix to this white paper.

7.1 Intended Use of Study Results

NEWR, as well as the methods presented in this study, are screening level tools designed to provide early guidance to water management planning processes at the building level. As such, these results should be interpreted as preliminary and approximate, with need for further refinement upon final design of any onsite NPR system. Although benefits of stormwater volume reduction discussed in Section 6 are extrapolatable to other buildings within the same community, other buildings will have different water demand and production profiles, resulting in different environmental impacts and costs.

8. REFERENCES

Arden, S., B. Morelli, S. Cashman, X. C. Ma, M. Jahne, and J. Garland. 2021. Onsite Non-potable Reuse for Large Buildings: Environmental and Economic Suitability as a Function of Building Characteristics and Location. *Water Research* 191. Elsevier: 116635.

BACWA. 2021. *Bay Area Clean Water Agencies Nutrient Reduction Study Group Annual Report*. Nutrient Watershed Permit Annual Report 2020. Bay Area Clean Water Agencies.

CAGIS. 2021. Buildings. Cincinnati Area Geographic Information System.

Cronshey, R. 1986. *Urban hydrology for small watersheds*. US Department of Agriculture, Soil Conservation Service, Engineering Division.

DataSF. 2020. Building Footprints. DataSF.

De Sousa, M. R. C., F. A. Montalto, and S. Spatari. 2012. Using Life Cycle Assessment to Evaluate Green and Grey Combined Sewer Overflow Control Strategies. *Journal of Industrial Ecology* 16: 901–913. doi:10.1111/j.1530-9290.2012.00534.x.

Fuller, S. K., and S. R. Petersen. 1996. *Life-Cycle Costing Manual for the Federal Energy Management Program*. U.S. Department of Commerce NIST handbook 135. Washington, D.C.: National Instititute of Standards and Technology.

Hendrickson, T. P., M. T. Nguyen, M. Sukardi, A. Miot, A. Horvath, and K. L. Nelson. 2015. Life-Cycle Energy Use and Greenhouse Gas Emissions of a Building-Scale Wastewater Treatment and Nonpotable Reuse System. *Environmental Science & Technology* 49: 10303–10311. doi:10.1021/acs.est.5b01677.

Morelli, B., S. Cashman, Ma, Cissy, Garland, Jay, Bless, Diana, and Jahne, Michael. 2019a. *Life Cycle Assessment and Cost Analysis of Distributed Mixed Wastewater and Graywater Treatment for Water Recycling in the Context of an Urban Case Study*. EPA/600/R-18/280. Cincinnati, OH: U.S. Environmental Protection Agency.

Morelli, B., S. Cashman, S. Arden, M. Ma Xin (Cissy), J. Turgeon, J. Garland, and D. Bless. 2019b. *Life Cycle Assessment and Cost Analysis of Municipal Wastewater Treatment Expansion Options for Food Waste Anaerobic Co-Digestion*. EPA/600/R-19/094. Washington, D.C.: U.S. Environmental Protection Agency.

Morelli, B., S. Cashman, X. (Cissy) Ma, J. Turgeon, S. Arden, and J. Garland. 2020. Environmental and cost benefits of co-digesting food waste at wastewater treatment facilities. *Water Science and Technology* 82: 227–241. doi:10.2166/wst.2020.104.

Rammal, M., and E. Berthier. 2020. Runoff Losses on Urban Surfaces during Frequent Rainfall Events: A Review of Observations and Modeling Attempts. *Water* 12. Multidisciplinary Digital Publishing Institute: 2777.

Rosato Jr., J. 2020. San Francisco Building Gives Water and Human Waste a Second Life. *NBC Bay Area*.

SFWPS. 2021. Water Re-use (Draft) Presentation presented at the Presentation for WateReuse and ERG, August.

Smith, A. L., L. B. Stadler, L. Cao, N. G. Love, L. Raskin, and J. Steven. 2014. Navigating Wastewater Energy Recovery Strategies: A Life Cycle Comparison of Wastewater Energy Recovery Strategies : Anaerobic Membrane Bioreactor and High Rate Activated Sludge with Anaerobic Digestion. *Environmental science & technology*: 5972–5981. doi:10.1021/es5006169.

Tavakol-Davani, H., R. Rahimi, S. J. Burian, C. A. Pomeroy, B. J. McPherson, and D. Apul. 2019. Combining Hydrologic Analysis and Life Cycle Assessment Approaches to Evaluate Sustainability of Water Infrastructure: Uncertainty Analysis. *Water* 11. Multidisciplinary Digital Publishing Institute: 2592. doi:10.3390/w11122592.

U.S. EPA. 2018. Emissions & Generation Resource Integrated Database (eGRID). U.S. Environmental Protection Agency.

Xue, X., S. Cashman, A. Gaglione, J. Mosley, L. Weiss, X. C. Ma, J. Cashdollar, and J. Garland. 2019. Holistic analysis of urban water systems in the Greater Cincinnati region: (1) life cycle assessment and cost implications. *Water Research X* 2: 100015. doi:10.1016/j.wroa.2018.100015.

Yoon, S.-H. 2016. *Membrane Bioreactor Processes*. Boca Raton, Florida: CRC Press.

APPENDIX A – Community Checklist

This checklist can be used by other communities to facilitate collection of data necessary to perform a similar analysis as that conducted in this Two City Pilot White Paper.

Target systems: Single buildings or building clusters in each city, consisting of up to approximately 1-6 large buildings, ideally on a single block and located within a combined sewer sewershed.

Building Characterization Data

NEWR Inputs

- ZIP code
- Building type (residential, commercial or mixed)
- Number of floors
- Number of occupants
- Building footprint
- Water heating – gas or electric
- What would non-potable water be used for?
    - Toilet
    - Laundry
    - Irrigated area
        - Area (square feet)
        - Type of vegetation (e.g., grass, trees, xeriscape, etc. or see guidance here)
    - Other Non-Potable Demand?

Ancillary Characterization Data (if available)

- Existing or projected per capita water use
- Existing or projected per capita wastewater generation
    - Ideally split between blackwater and greywater

Utility Characterization

Drinking Water

- Rate/rate structure

Wastewater

- Rate/rate structure

Stormwater

- Rate/rate structure

LCA Metric Evaluation

- If available, LCA analysis of local centralized drinking water and wastewater infrastructure

Combined Sewer/Stormwater System

- At least 5 years of daily rainfall data from the nearest weather station.
- Have any local environmental or economic studies of CSO mitigation been performed?

- In order to characterize potential benefits to CSOs from implementation of RWH, populate the following table with characteristics from 1 or more CSO sewersheds. As a measure of "large buildings" (see discussion in the paper) we use a value of 5,000 ft^2, however this threshold can be modified as needed to match local objectives. For rooftops and rooftop area, consideration should be given to whether stormwater generated from those buildings is currently treated (detained or retained) or not. Buildings with little to no existing stormwater treatment have the greatest potential for a RWH to reduce peak flows within the combined sewer system.

CSO Sewershed	Area (acres)	# of Rooftops > 5,000 ft^2	Total Area of Rooftops > 5,000 ft^2	Typical # of Events per Year	Typical Storm Event Size or Threshold (in)	Average Annual Overflow Volume

- If wanting to estimate the fraction of wastewater or sludge that can be abstracted from the central sewer system, compile data in the following table:

Sewershed	Dry Weather Flow (MGD)	Dry Weather Flow TN (mg/L)	Dry Weather Flow TP (mg/L)	TN (lb/d)	TP (lb/d)