# Analyzing Economic Feasibility of Greywater Systems: A San Francisco Case Study

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## ABSTRACT

With the issue of water scarcity, the threat of climate change, people need methods of controlling their water consumption. Greywater systems like membrane bioreactors (MBR) and constructed wetlands (CW) offer a solution; but will only adopt these systems if they are economically feasible. To measure for economic feasibility, this paper uses a cost-benefit analysis that uses total costs associated with capital, operation, and maintenance costs alongside benefits from water savings to evaluate both systems for payback period, cost-benefit ratio, and net present value on a 20-year lifetime of the system. Both the single-family residence MBR and CW systems were found to be not economically feasible due to negative NPVs and payback periods larger than system lifetime. Feasibility was also analyzed for economies of scale by evaluating both systems fit for a single-family, multi-family, and commercial residence. The results found that among the six systems, the multi-family CW and MBR systems were the most feasible with payback periods of 4 years and NPVs of $120,563, and $161,362. Feasibility was also evaluated for the single residence MBR under 3 scenarios of increasing water rates. The study found that Scenario 3 with a 7.5% increase in water rates provided the most benefit and lowered the payback period of the system by 9 years when compared to the Scenario 1- BAU water rate projection. These results suggest that currently, the most economically feasible systems are multi-family MBR and CW systems, but more systems could become feasible as water rates rise in the future.

## KEYWORDS

Membrane Bioreactor, Constructed Wetlands, Cost-Benefit Analysis, Payback Period, Net Present Value

# INTRODUCTION

One of the most pressing issues facing the world is water scarcity. Two-thirds of the global population was living under conditions of severe water scarcity at least 1 month of the year (Mekonnen and Hoekstra 2016). So how did water, something so vital to all life on earth, become so scarce? There is a finite amount of freshwater that is accessible for use, and the increasing stress from climate change, pollution, and food industry needs has exacerbated the supply. Additionally, the world population is estimated to increase by 2 billion in the next 30 years, further exhausting this global water crisis (UN DESA, 2019). For this study, I focused on San Francisco, California.

The water crisis, although a global phenomenon, strongly impacted California residents between 2012-2016 when California experienced one of its worst droughts in state history (Ullrich et al. 2018). At the drought's peak in 2015, Governor Jerry Brown issued an executive order mandating the CA Water Board to impose restrictions on water use to achieve a 25% reduction from 2013 in potable urban water usage (Executive Order B-29-2015). Residents responded to this in many different ways, from buying water-efficient washers and toilets to adopting drought-tolerant landscapes. Luckily for California, the state was able to rely on its groundwater resources when the drought led to a shortage of available surface water. This drought demonstrated California's vulnerability and how if these unsustainable practices were to persist, there would not be sufficient groundwater in supply to rely on(Ojha et al. 2018). Another outcome of this drought was the public realization of California's fragile water supply and the need to manage daily water consumption and implement water conservation techniques. Of the systems used to reduce water consumption, researchers have stated the best systems are those that utilize existing infrastructure and innovative efficient technology, leading us to further investigate greywater systems (Gleick 2003).

Greywater systems utilize innovative technology and existing infrastructure that enables them to be a viable option for reducing water consumption. Consequentially, because GW systems are a relatively new solution, one of the biggest factors affecting their adoption is the consumer's lack of information. California plumbing code (2010) defines greywater as untreated wastewater that has not been contaminated by toilet discharge or other infectious sources that may present a health and safety threat. For example, greywater includes wastewater from showers and laundry machines but excludes wastewater from kitchen sinks, toilets, and dish-washing appliances. While there are various kinds of greywater systems on the market, a consumer looking to finance a greywater system would struggle to find information about which system would be most feasible, especially given the different costs associated with each system and how they vary respective to residence size.

This study will make a significant contribution to both research and policy by addressing this gap in public knowledge. The analysis done in this study will provide insight into the economic feasibility of greywater systems in San Francisco.

## BACKGROUND

### San Francisco Ordinances

The choice of San Francisco as a study cite was in part due to San Francisco's initiative towards implementing greywater systems in the city. In 2012, San Francisco adopted an ordinance allowing for the treatment and use of alternate water sources for non-potable use in small buildings ("San Francisco Public Utilities Commission: Non-potable Water Program" n.d.). Then in 2015, to help progress with water conservation efforts, San Francisco mandated that all new construction projects greater than 250,000 square ft. install onsite-non-potable water systems to treat and reuse greywater and rainwater while subjecting projects of sizes between 40,000 and 250,000 square ft. to start budgeting for the adoption of this system as well. This program also allocates funding for buildings under the mandate by allowing applicants to receive up to $500,000 depending on how many gallons of water the new system will treat. Additionally, San Francisco has a Recycled Water Ordinance that requires buildings 40,000 square feet and larger to in the designated areas to implement a recycled water system (Brears 2020). This exemplifies the progress that has been made towards the adoption of water reuse systems, but the motivation behind the San Francisco mandates was water conservation and efficiency and for the adoption of greywater systems to become widespread, the systems need to be economically feasible for the consumer.

### Literature Review

*Greywater treatment systems on the market:*

Before addressing the process of analyzing economic feasibility, I will address a few of the greywater treatment/ reuse systems that are available on the market. While, there is no shortage of greywater systems on the market, but not all are compatible in the context of implementing residential GW systems in San Francisco.

Sand filter systems are one type of greywater system that has become popularly utilized. These systems function by purifying water in three different stages. First, the greywater goes through a filtration process where particles are physically strained from the wastewater. Then the process shifts to chemical sorption in which contaminants are drawn to stick towards the surface of the sand and then finally the treated water flows through an assimilation stage where aerobic microbes use a nitrification process to consume these nutrients and convert them to volatile effluent (Abdel-Shafy et al. 2014). While this system is inexpensive (Li et al. 2010), researchers doubt the quality of effluent and recommend the sand filter process be used in combination with other treatment systems (Li et al. 2009). These systems also have a chronic clogging issue which inconveniences the consumer who has to consistently maintain their system and pay the added costs of the maintenance (Ghunmi et al. 2011).

Another widely used greywater system is the constructed wetlands system (Figure 1). The treatment process for this system consists of three stages with the greywater initially going through a physical process similar to sand filters where the main pollutant is filtered through porous sand. Next, the treated water is processed under a chemical ion exchange and lastly, the treated water undergoes microbial functions through the natural elements of the plants (Kadewa et al. 2010). Although constructed wetlands are suitable for both small and large residential sites, they can also take excessive space and need constant maintenance by the user ("Constructed Wetlands Information" n.d.).

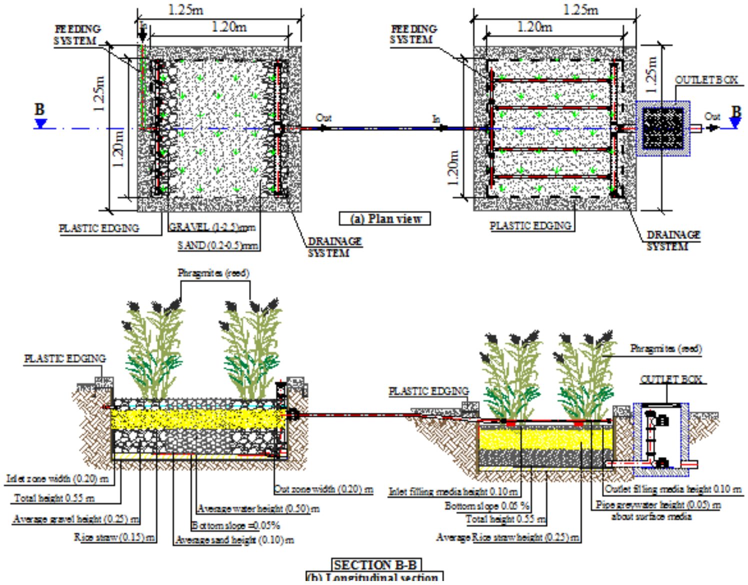


**Figure 1*:*** Schematic of Example Constructed Wetlands System (Abdel-Shafy et al. 2013)

Membrane bioreactor systems (Figure 2) are the most complex for onsite residential greywater treatment such that they require the water to undergo several stages to get to the final effluent, but in turn also supply the best quality effluent (in terms of bacteria, pathogens, and viruses) (Winward et al. 2008).

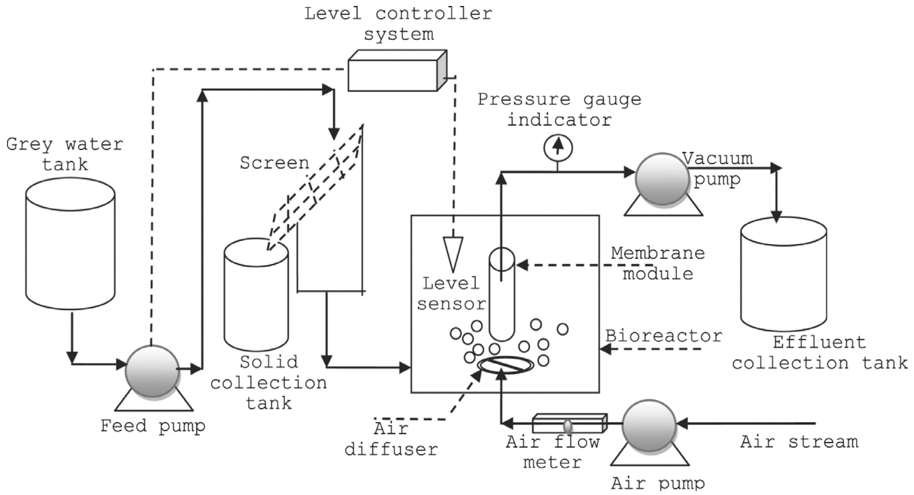


**Figure 2:** Example of Membrane Bioreactor Flow (Bani-Melhem et al. 2015)

Membrane bioreactor systems utilize porous membranes in order to facilitate ultrafiltration and microfiltration processes that function through size exclusion but ultrafiltration is used to separate "large, dissolved solute molecules and suspended colloidal particles" and microfiltration is used for suspended solid separation and are made to operate at high suspended solids concentrations. (Stephenson et al. 2000, Penn et al. 2012).

Aside from the system's effluent water quality, MBR's compact design also prove beneficial in densely populated areas and because they can be produced in various sizes, they are suitable for both large and small residential sites. Two flaws with MBR systems are that their filters experience fouling which causes pre-meditated replacement and their complex design requires costly annual operation and maintenance. To show the feasibility of two systems of varying benefits, this study evaluates both the MBR system and the CW system.

### *Evaluating Economic Impact of Greywater Systems*

The bulk of the literature evaluating economic impacts of onsite residential greywater systems utilize cost-benefit analyses to evaluate costs over the lifetime of the system using metrics of net present value and payback period (Memon et al. 2005, Friedler and Hadari 2006, Juan et al. 2016, Atanasova et al. 2017). The value in evaluating costs throughout the lifetime of the system is that it allows for a holistic view of the overall cost by including reoccurring costs (such as maintenance and operating costs) and not only the one-time costs that are inflicted on the consumer at the point of installation.

When assessing the feasibility of membrane bioreactor systems across multi-storey buildings, Friedler and Hadari (2006) found that payback periods were very dependent on the size of the system in use and in their study site, MBR systems did not become feasible until 37 stories or more. Similarly, Atanasova et al. found that in their study of a hotel in Lloret de Mar, Spain, MBR systems were able to reduce wastewater generation by 30% with the system having a payback period of just 3 years given the hotel using more than $30m^3$/day. This study also estimated a payback period of 7 years such that a residence was using $5m^3$/ day. Juan et al. imposed a water rate scenario-based cost-benefit analysis where three scenarios were used. The first scenario assumed constant water rates within the 20-year lifetime period, the second assumed water rates remained unchanged from the 1st to the 5th year and then the rates surged by 30% from the 6th to the 20th, and the third scenario imposed a 50% price surge for the 1st to the 5th year and a 100% price surge from the 10th to the 11th year with a 500% surge from the 11th to 20th year.

Following the status quo from the literature, this study will use the metrics of net present value, payback period, and benefit-cost ratio to measure the feasibility of the CW and MBR system while using sensitivity analyses to attribute the impacts of changing water rates and residence size on feasibility.

## METHODS

This study utilized a cost-benefit model to analyze the feasibility of MBR and CW greywater systems. The cost-benefit analysis is used for its ability to account for the various expenses incurred throughout the lifetime of the system and adjust to the annual water savings received as a result of adopting the GW system. Researchers (Li et al. 2010, Juan et al. 2016, Atanasova et al. 2017) in the greywater sector also utilize cost-benefit analyses to estimate economic feasibility. My selection of San Francisco as a study site was motivated on three factors such that San Francisco ordinances pushing the use of greywater technology among large commercial buildings show the growing prevalence there; the rising water rates there have/will incentivize residents to look towards water-saving practices, and the assumption that residents of San Francisco would likely have the capital available to invest in a greywater system.

### Data collection

To collect data for my feasibility model, I utilized data from internet research, interviews with suppliers and contractors of greywater treatment systems, manuals, and accessible government data. The parameters for the study including avg energy cost, avg water demand per capita, etc. can be seen in Table 1.

**Table 1. Model Parameters**

| Parameters | Unit | Value | Reference |
|---|---|---|---|
| Toilet flushing | L/d per capita | 59 | DeOreo 2011, DeOreo & Hayden 2008 |
| Kitchen sinks | L/d per capita | 17 | DeOreo 2011, DeOreo & Hayden 2008 |
| Laundry machine | L/d per capita | 52 | DeOreo 2011, DeOreo & Hayden 2008 |
| Showers and bathtubs | L/d per capita | 45 | DeOreo 2011, DeOreo & Hayden 2008 |
| Avg electricity rate in San Francisco | $/kwh | .214 | US Bureau of Labor Statistics 2020 |
| Wastewater flow factor | % | 90 | San Francisco Water Power and Sewer Service Rate Schedules and Fees (2019-2020) |
| Greywater system output | Gallons/day | Varies from system to system | |
| Discount rate | % | 3 | Lavappa and Kneifel 2020 |
| Avg. water use in San Francisco per capita | Gallons/day | 40 | SFPUC Water Resources Division Annual Report 2017 |
| Gallons to CCF conversion | CCF/gallon | 1/748 | San Francisco Water Power and Sewer Service Rate Schedules and Fees (2019-2020) |
| Water delivery rates (tier 1 and tier 2) – years 2020,2021, 2022 | $/ CCF month | SR: tier 1 (first 4 units): $7.65, $8.68, $9.60<br>SR: tier 2 (additional units): $9.61, $10.51, $10.71<br>MF: tier 1 (first 3 units): $7.94, $8.73, $9.60<br>MF: tier 2 (additional units): $9.73, $10.23, $10.76<br>C: all units: $9.14, $9.81, $10.55 | San Francisco Water Power and Sewer Service Rate Schedules and Fees (2019-2020) |
| Wastewater rates (2020, 2021, 2022) | $/ CCF month | $13.88, $14.89, $15.97 | San Francisco Water Power and Sewer Service Rate Schedules and Fees (2019-2020) |

I obtained info relevant to capital expenditures of the system (CAPEX), the money spent the first year when the system is installed, and operation expenditures (OPEX), which for the purposes of this study included any annual cost that was important to the operation of the system. CAPEX and OPEX (Table 2 and Table 3) prices were collected for both MBR and CW systems for a large single-family residence (SR), multi-family residence (MF), and commercial sized residence (C). Both of the commercial buildings are buildings in San Francisco and data was collected by reaching out to the respective facilities and academic case studies. The benefits of the systems were calculated with respect to water saved from using and wastewater saved from going to the sewage, so each saving was calculated with respect to water delivery and wastewater rates. Current projections for these rates only go to 2022 (see Table 1), with observed 110% annual price escalations since 2018. This pattern of 1.1% annual price escalations for 5 years was then applied to the 20-year lifetime of the systems.

**Table 2. Overview of MBR Costs**

| Category of Cost | Type of Cost and Replacement Frequency if Applicable | Value | Reference |
|---|---|---|---|
| CAPEX: | System Cost (including labor) | SR: $4,830<br>MF: $20,652<br>C: $320,000 | Fletcher et al. 2007; info from contractor |
| CAPEX: Installation | Installation retrofitting piping & plumbing | SR, MF: Included with system costs<br>C: $160,000 | Fletcher et al. 2007; info from contractor |
| CAPEX: Installation | Electrical wiring | SR, MF: Included with system costs<br>C: $90,000 | " " |
| OPEX | Replacement Membrane(s) (Every 7 years) | $1295/membrane | Peconic Green Growth: BioBarrier–N MBR Series |
| OPEX | Replacement Pumps (year 5, 10, 15, 20) | $200/replacement;<br>$594 x (flow rate/day)$^{.0286}$ | Fletcher et al. 2007; Friedler and Hadari 2006 |
| OPEX | Replacement Screen (Every 10 years) | $1090/screen | Fletcher et al. 2007 |
| OPEX | Replacement Blower (Every 10 years) | $500/blower | Peconic Green Growth: BioBarrier– |

| | | | |
|---|---|---|---|
| OPEX | Replacement Tank (Every 20 years) | $1000+520(Volume of Tank) | N MBR Series<br>Fletcher et al. 2007 |
| OPEX | Electrical costs | 1.5 kwh/$m^3$ | Friedler and Hadari 2006 |
| OPEX | Other Cleaning and Maintenance Costs | $196.2/ (.5$m^3$/day)<br>Cumulative OPEX for C: $55000/year | Jabornig 2014 |

**Table 3. Overview of Constructed Wetlands**

| Category of Cost | Type of Cost | Cost in $ | Reference |
|---|---|---|---|
| CAPEX | System Cost (Includes Labor) | SR: $2,500<br>MF: $20,543<br>C:$1,000,000 | SR, MF: Yu et al. 2013, de Simone Souza et al. 2017<br>C: Contractor Info |
| CAPEX | Installation/Construction Materials:<br>Fine plastic mesh<br>Impermeable linear<br>Valves<br>Check Valve (backflow preventer)<br>Sand<br>Gravel<br>Mulch<br>Vegetation | Included in System Cost | “ ” |
| OPEX | Energy Costs | SR, MF: 0.014 kwh/$m^3$<br>C: 4500(kwh /ML/year) | Zadeh et al. 2013, Hendrickson et al. 2015 |
| OPEX | General Operation and Maintenance | SR: $150/yr.<br>MF:$348/yr.<br>C: $250,000/yr. | SR, MF: Yu et al. 2013<br>C: Contractor Info, Hendrickson et al. 2015 |
| OPEX | Annual Costs | SR: $450<br>MF: $1,492.50<br>C: $1,504.20 | SR: Yu et al. 2013<br>MF, C: Zadeh et al. 2013 |

## Data Analysis

### *Feasibility of single-family residence MBR system v. CW system*

To compare the feasibility of each system, the systems were analyzed on a 20-year lifetime period to find total annual costs $C_n$, adjusted with the discount rate to find Net Present Value of the annual costs as shown in Equation 1.

$$C_n = \frac{C_{CAPEX\ n} + C_{OPEX\ n}}{\left(1 + \frac{r}{100}\right)^n} \qquad \textit{Equation 1}$$

Where:

$C_n$ = Total annual costs
r = Economic discount rate (%)
n = Time period
$C_{CAPEX\ n}$= Sum of capital expenditures in year, n.
$C_{OPEX\ n}$ = Sum of operational expenditures in year, n.

The benefits of adopting the greywater system, were calculated to include the annual savings ( $S_{W_n}$, Equation 2) that the consumer receives from the water they are able to reuse for non-potable needs as a result of the implementation of the greywater system; as well as the savings ($S_{WW_n}$, Equation 3) the consumer would receive from sending less water to the sewer.

$$S_{W_n} = 12(W_{tier1_n}\,(O_{tier\ 1}) + W_{tier2_n}\,(O_{tier\ 2})) \qquad \textit{Equation 2}$$

Where:

$S_{W_n}$= Annual water savings
$W_{tier1_n}$ = Water rate for tier 1 water usage in year, n
$W_{tier2_n}$= Water rate for tier 2 water usage in year, n
$O_{tier\ 1}$ = GW system output that fits in tier 1
$O_{tier\ 2}$ = GW system output that fits in tier 1

$$S_{WW_n} = 12(WW_n\,(F_{ww}(O))) \qquad \textit{Equation 3}$$

Where:

$S_{WW_n}$= Annual wastewater savings
$WW_n$= Rate for wastewater disposal
$F_{ww}$ = Wastewater flow factor
$O$ = GW output of system

The calculation of total annual benefit ($B_n$, Equation 4) from each greywater system combined the total annual water savings with the total annual wastewater savings and adjusted the savings with a discount rate to reflect net present value. The calculation for annual benefit also included local government aid given to consumers who install large commercial greywater systems and allows for adjustment for government incentive programs.

$$B_n = G + \left(\frac{S_{W_n} + S_{WW\,n}}{\left(1+\frac{r}{100}\right)^n}\right) \qquad \textit{Equation 4}$$

Where:

$B_n$ = Total annual benefit
$G$ = Government grant funds (only available for capital expenses in large commercial greywater systems for)

To further understand the feasibility of each system, I calculated the annual cash flow or Annual Net Savings (Equation 5), by summing the total annual benefit and the total annual cost. This annual net savings metric can then be used to indicate the varying annual expenses or savings the consumer would incur throughout the lifetime of the system.

$$\text{Annual Net Savings: } A_n = C_n + B_n \qquad \textit{Equation 5}$$

Given the Annual Net Savings, the overall Net Present Value ( $NPV_l$, Equation 6) of both annual costs and benefits was calculated to serve as metric of how much money the consumer of each system would lose or save by adopting the respective system, in 2020 dollars. The Net Present Value is dependent on the lifetime assigned to the system and for this analysis; a lifetime of 20 years was assumed for both systems.

$$NPV_l = \sum_{n=0}^{l} A_n \text{ or } NPV_l = \sum_{n=0}^{l} C_n + B_n \qquad \textit{Equation 6}$$

The feasibility of the two systems was also evaluated through the metrics of its Benefit-Cost ratio and payback period. The Benefit-Cost ratio ($R_{B/C}$, Equation 7) was calculated by adding together the Annual Net Savings for each year of the lifetime of the system. The closer to 0 the ratio is, the less feasible the system is since the consumer would be absorbing more of the costs and the closer the ratio is to 1, the more feasible the system is, with values above 1 suggesting that the consumer effectively makes money from adopting the system.

$$R_{B/C} = \frac{\left|\sum_{n=0}^{l} B_n\right|}{\left|\sum_{n=0}^{l} C_n\right|}$$ *Equation 7*

Where:

$l$ = Lifetime of system
$R_{B/C}$ = Benefit-Cost ratio

The calculation of payback period (PP, Equation 8) serves as a metric showing how long it takes to pay off a system, such that the lower the value the better for the consumer as they will start reaping the economic benefits of the system sooner. Payback period was analyzed with a 40-year system lifetime to ensure accuracy of value.

$$\text{PP} = n \text{ when } NPV \text{ is} > 0$$ *Equation 8*

Where:

$PP$ = payback period

*Sensitivity analysis- effect of changing water rates on feasibility*

**Table 4. Water Rates Sensitivity Analysis**

| **Scenario** | **Rate Increase** |
|---|---|
| Scenario 1: BAU | 110% annual increase for 5 years, every 10 years. (Price escalations in periods 8-12, 18-22, and 38-40) |
| Scenario 2 | 5% annual increase in both tiers of water delivery and wastewater rates |
| Scenario 3 | 7.5% annual increase in both tiers of water delivery and wastewater rates |

The analysis of the single residence MBR system with respect to changing water rates was done with 3 scenarios (Table 4). The first scenario accounts for a business as usual model with the third scenario accounting for the most dramatic increases in water rates throughout the 20-year lifetime of the system. Ultimately, the changing water rates impact the benefits of the MBR system. The single residence system was then analyzed with respect to the metrics of $NPV$, PP and $R_{B/C}$ to see how each scenario would impact feasibility, given the altered benefits and savings.

*Sensitivity analysis- residential economies of scale*

I analyzed both MBR systems and CW systems for a system sized for multiple families and for commercially-sized systems. To ensure equality among systems analyzed, both multi-family systems were sized to a 50-person population equivalence, and both commercial systems treated 800,000 gallons a year. The analysis for each of the additional 4 systems mirrored that of the single residential systems, with Scenario 1 and the same metrics used .

## RESULTS

### Results of the single residence MBR v. CW comparison

I evaluated the feasibility of both the single residence MBR and CW systems to find each system's Net Present Value, payback period, and Benefit-Cost ratio. The output of the analysis found that the Constructed Wetlands residential system had a Net Present Value, given a 20-year lifetime, of -$1571.5; a payback period of 29 years; and a Benefit-Cost ratio of .76. Conversely, the output for the residential MBR system found that the system had an NPV of $-2309.38, a payback period of 26 years, and a Benefit-Cost ratio of .13. It's important to note that both systems had payback periods above system lifetime, negative NPVs, and $R_{B/C}$ values less than 1. Table 5 summarizes the outputs and differences between the two systems are shown in Table 5. The annual net savings for each of the systems is visualized in Figure 1.

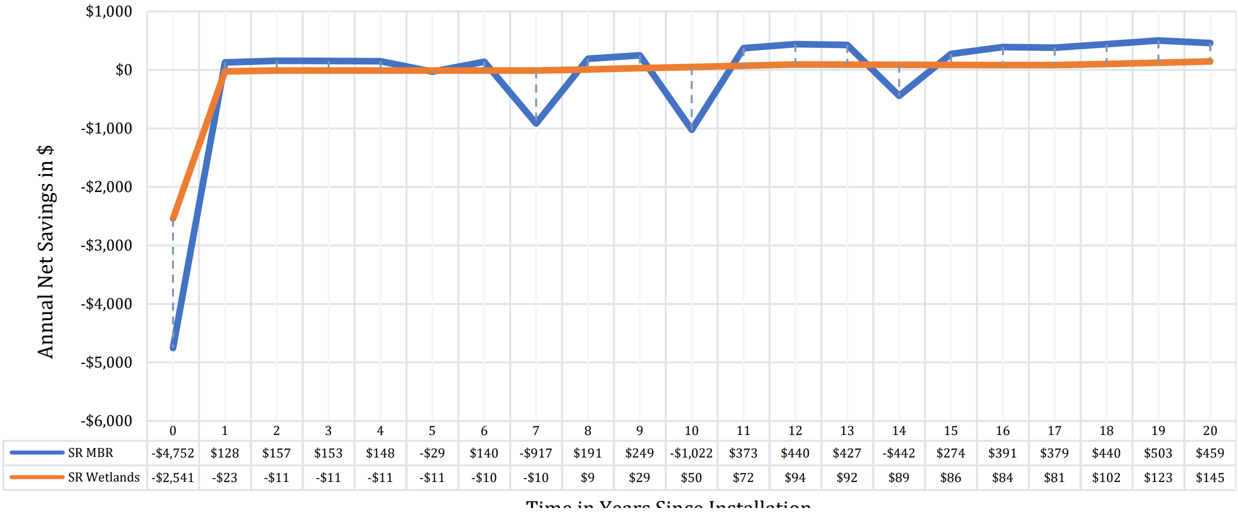


**Figure 3. Comparison of Annual Net Savings (Single Family Residential MBR v CW)**

**Table 5. Single Residence MBR v CW**

| | **Single Residence MBR** | **Single Residence CW** | **Single MBR v. Single Residence** |
|---|---|---|---|
| NPV | -$2,309.38 | -$1,571.50 | CW: +738.88 |
| Payback period | 26 | 29 years | MBR: 3 years less |
| Benefit-Cost ratio | 0.130 | 0.76 | CW: 5.4x larger |

## Results for SR-MBR under changing water rate scenarios

**Table 6. Water Rates Sensitivity Analysis Metrics for Single Residence MBR**

| **Scenario** | **Payback Period** | **NPV** | $R_{B/C}$ |
|---|---|---|---|
| Scenario 1 (BAU) | 26 | -$2,309.38 | .87 |
| Scenario 2 (5% annual increase) | 23 | -$299.21 | .98 |
| Scenario 3 (7.5% annual increase) | 17 | $3,945.45 | 1.22 |

To analyze how changing water rates would impact GW savings, I considered three scenarios with varying degrees of annual water rate increases. Of the three scenarios, the business as usual projection had the largest payback period (Figure 4) and the smallest Benefit-Cost ratio (Figure 5). Only Scenario 3 had a payback period below the system lifetime (Figure 4) and a positive NPV (Table 6). Table 6 shows the output of feasibility metrics with every scenario, and Figure 6 exemplifies the differences in the annual net savings for each scenario.

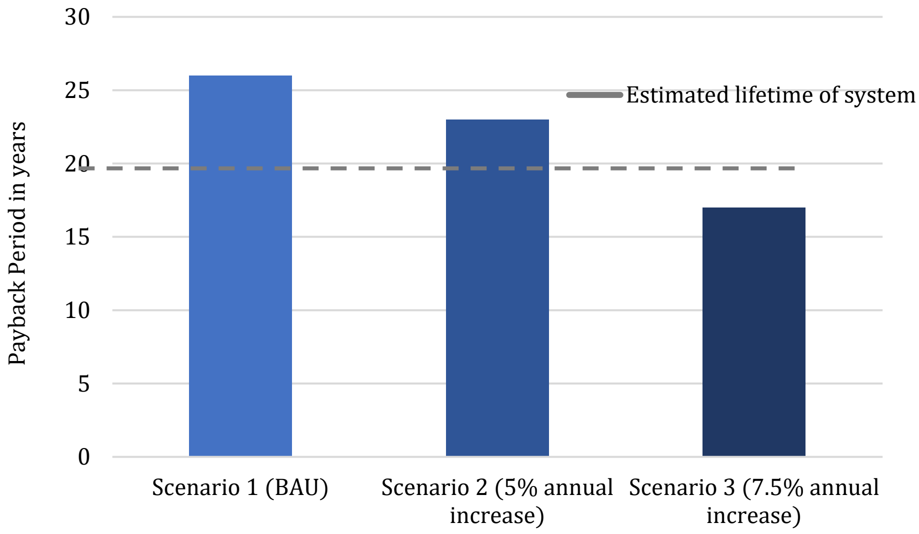


**Figure 4. Comparing payback periods of each water rate scenario.** 20 year lifetime was assumed for each scenario.

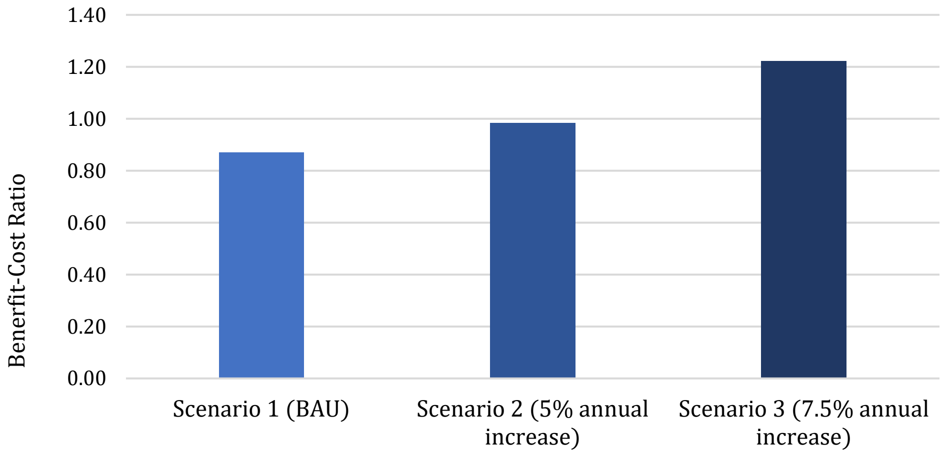
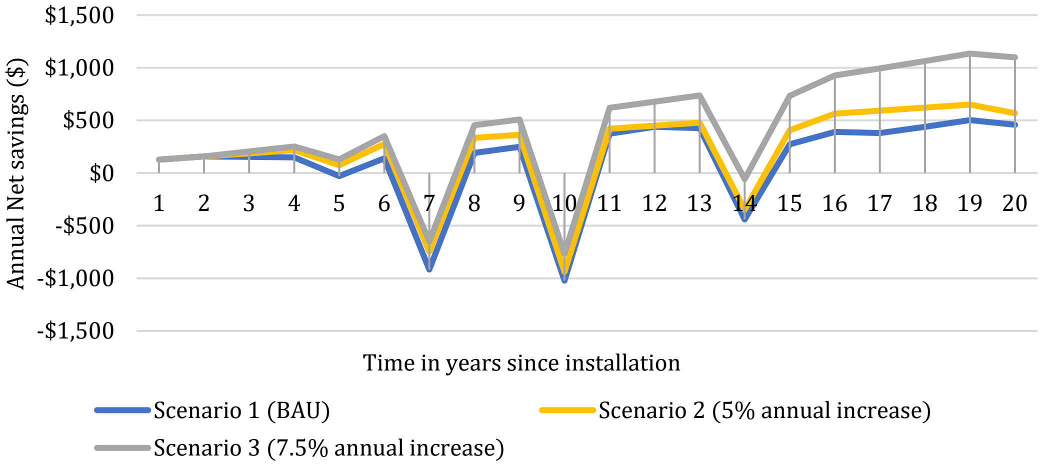


**Figure 5. Comparing Benefit-Cost Ratio of each water rate scenario.** Analyzed over 20 year lifetime where each scenario represents annual increase in both water delivery and wastewater rates.



**Results for feasibility with respect to economies of scale**

By analyzing both the MBR and CW systems at larger residential sizes, I was able to see the impact of facility/residence size on the economic feasibility of the respective greywater system. Table 7 summarizes the metric outputs for each system considered.

**Table 7. Outputs of metrics for residential size sensitivity analysis**

| Type of Residence | Payback Period | NPV | $R_{B/C}$ |
|---|---|---|---|
| Single Family Residence (MBR) | 26 | -$2,309.4 | 0.87 |
| Single Family Residence (CW) | 29 | -$1,571.50 | 0.76 |
| Multi-family Residence (MBR) | 4 | $161,362.83 | 2.15 |
| Multi-family Residence (CW) | 4 | $120,563.41 | 3.42 |
| Commercial Residence (MBR) | 30 | -$330,670.31 | 0.77 |
| Commercial Residence (CW) | >40 | -$1,837,161.33 | 0.30 |

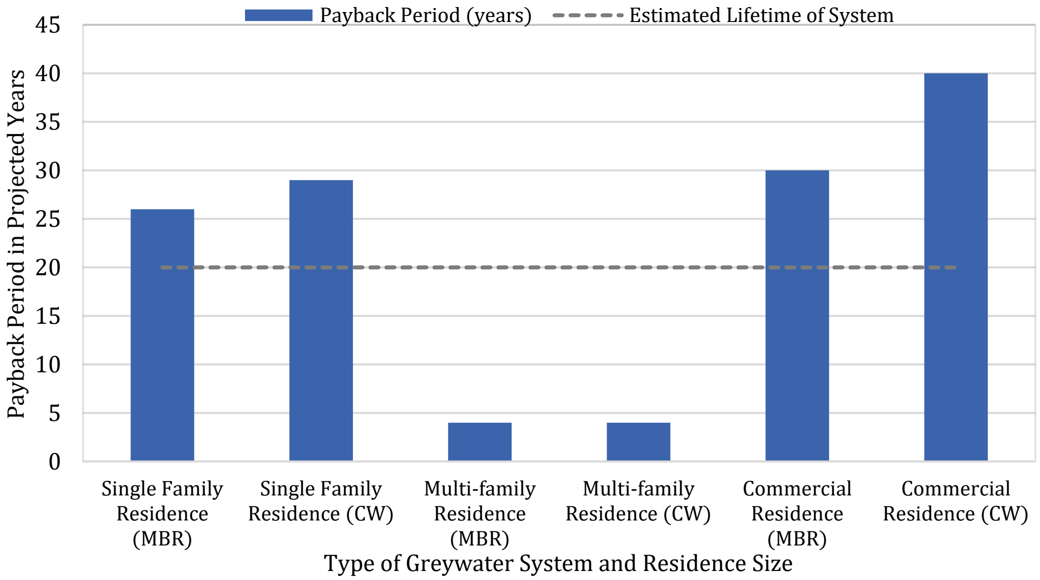


**Figure 7. Comparing payback periods of each residential system.** Analysis assumed 20 year lifetime for each system.

The only systems that had payback periods below the system lifetime of 20 years were the two Multi-family residence systems (Figure 7). As shown by Table 7, these two systems were the only systems of the six to have a positive NPV and an $R_{B/C} > 1$. Both the commercial MBR and the commercial CW systems did not meet any of the feasibility metrics, so they were both analyzed additionally on a 40-year lifetime scale to see how more time would impact annual net savings and, therefore, feasibility. As can be seen in Figure 8, both systems are projected to increase dramatically within the 20 years following the 20-year life period.

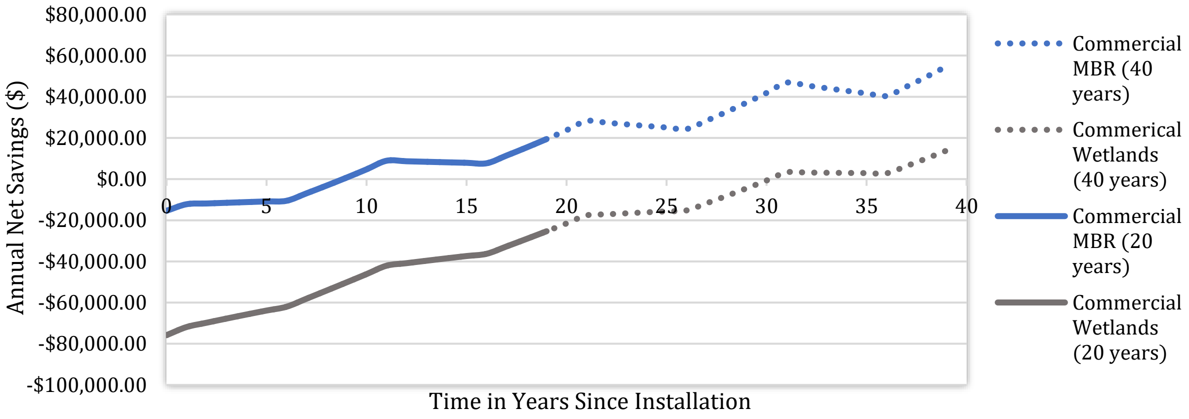


**Figure 8: Projected Annual Net Savings over 40 year lifetime (MBR v. CW).** 40 yr. lifetime was projected by mirroring 20 year lifetime analysis and continuing water rate trend.

## DISCUSSION

With the uncertainty of future water rates and the looming threat of freshwater shortages, there is a substantial need for guidance towards which GW systems are most feasible. This research demonstrates the viability of greywater reuse systems to the consumer. Since the discovery of the submerged membrane bioreactor in the 1990s, membrane bioreactors had functioned mainly for centralized wastewater treatment, and only through recent advancements in technology has the membrane bioreactor been able to function in other applications like greywater (Hai et al. 2019). While there are many options for greywater systems on the market, researchers ((Li et al. 2010, Capodaglio et al. 2017, Hai et al. 2019)) have emphasized the overwhelming benefits of biological systems such as constructed wetlands and membrane bioreactor systems. With the consumer having the safety of mind knowing that both these greywater systems will satisfy respective water reuse standards, the consumer needs to know under which system will provide them with the most economic benefit and how that changes with respect to residence size and water rates. This study also found significant benefits from adopting these systems, specifically for the systems fit for multiple families and under scenarios assuming dramatic annual rises in water delivery and wastewater rates.

### Feasibility of small-scale systems

When analyzing the economic feasibility of an MBR system v a constructed wetlands system, the results leaned heavily in favor of the small-scale MBR system over the small-scale constructed system. This finding directly contradicts the popular notion among the literature that Constructed Wetlands are more favorable on a smaller scale due to lower capital investments and annual maintenance costs (Yu et al. 2015). The $R_{B/C}$'s presented in the results suggest that there are more benefits to adopting a small scale MBR system than there are to selecting a small scale CW. Still the NPVs for each system indicate that the adoption of the MBR system would effectively allow the consumer to be $739 less in debt at the end of the system's lifetime. Although the results clearly showed the adoption of the MBR system being more advantageous, neither system is feasible to the consumer when they would not financially benefit from the system and would effectively pay more by adopting the greywater systems. As seen in Figure 1, in period 0, where capital costs are assumed, the CW system is noticeably less costly than the MBR system, but over time the wastewater savings offered from the CW system could not outweigh the annual OPEX costs.

### Increased economic feasibility with increased water rates scenario

Due to urban water scarcity and climate change mitigation costs, future water rates are likely to be uncertain. Using the inputs for the single residence MBR analysis, feasibility was analyzed with respect to two additional scenarios that projected increases in the annual water and wastewater rates. The results suggested that under Scenario 3, where the annual growth rate was set to 7.5%, the single residence MBR was feasible with a positive NPV, a Benefit-Cost ratio > 1, and a payback period less than the system lifetime. Given that historical rates from 2008-2016 showed water price escalation rates of 6% in Oakland, CA and 7.3% in Seattle, WA (*Water and Wastewater Annual Price Escalation Rates for Selected Cities across the United States* 2017); Scenario 3 provides projections of water rates that are justifiable under past instances. Because Scenario 3 is already present in some cities, one can believe that other cities will also start to resemble this growth rate in water rates, which would effectively make MBR systems more economically feasible.

## Economies of scale

Considering the many different styles of residences found throughout California and specifically San Francisco, it is vital to analyze feasibility for residence of different sizes. The results suggested that of the six scenarios analyzed, only the mid-sized multi-family MBR and CW systems met the metrics for feasibility, and all of the MBR systems proved to be more feasible than their CW counterpart on every residence size level. Both of these systems had small payback periods of four years, and NPVs well above $100,000. Using the NPVs for the two multi-family systems, the MBR system would be more feasible with about $40,000 more in NPV, suggesting more benefits for the consumer. This finding is in agreeance with the literature that states that the benefits of economies of scale for the MBR system are only significant up until a 50 people population equivalent (Fletcher et al. 2007). The results in this study also suggested that GW systems fitted for larger commercial buildings were not feasible since the metrics implied the adoption of both systems would not be paid off within the lifetime of the system and would in the consumer paying hundreds of thousands of dollars in costs that wouldn't be returned. This finding contradicts research findings in the literature that state MBR systems become feasible after exceeding 20 stories or 37 stories (Friedler and Hadari 2006, Imteaz and Shanableh 2012).

One explanation for why the results did not suggest that GW systems became most feasible at the commercial scale is that this scale demands systems of larger complexity, which are likely able to withstand longer than the assigned 20 year lifetime. Figure 6 visually represents the annual net savings for both systems under a 40- year lifetime and the trends suggests that MBR system would likely become very profitable with a high NPV if this higher lifetime of the system was assumed.

## Broader Implications

This study suggests that by adopting a GW system, multi-family residence owners would effectively earn money from the savings while significantly reducing their water demand. This is especially impactful for the abundance of apartment complexes of this size found in San Francisco.

The results of this study also suggest the growing viability and feasibility of these greywater systems as result of growing water rates in San Francisco and throughout the nation. With future advancements in research and development lowering the burden of capital costs on CW systems and operation costs on MBR systems, it is expected that more systems of all sizes will become economically feasible, aiding with the water scarcity crisis.

### Limitations and Future Directions

Given the scale of this project, there were many limitations in capacity and time. Future research for the impact of residence sizes on feasibility, would benefit from the incorporation of more building sizes in San Francisco to find a range at which the size of residence would benefit most from adopting a GW system. Additionally, both of the commercially sizes systems were very complex and incorporated more than just the CW or MBR systems resulting in the possibility of overestimation of each systems' expenses.

In terms of future directions, San Francisco or California could start incentivizing single family residences to adopt small scale greywater systems by offering grants that help offset the burden of capital expenses, similar to programs already in place in SF for commercial buildings. Greywater incentivization programs could also be modeled similar to those of solar panel programs where homeowners are eligible to have 1/4th of their system paid via tax credit ("Go Solar California" 2016). Future studies research economic feasibility would benefit from including GHG emissions and the environmental benefit of saving water to the costs and benefits of adopting GW systems. Additionally, this study shows the greater economic feasibility of MBR systems when compared to CW systems, suggesting future research and development should be focused towards making MBR systems more efficient and thus even more economically feasible.

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