Financial analysis of decentralized water reuse systems in mission critical facilities at U.S. Army installations†

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Given increased frequency of droughts and other extreme events exacerbated by climate change, decentralized water reuse is being increasingly considered as a key opportunity for increasing resiliency and sustainability by reducing net municipal water demand and emergency resupply needs. Initial building scale approaches, such as onsite treatment and reuse of wastewater for toilet flushing has not been economically favorable in many cases. Return on investment (ROI) of such projects is limited by the capital and annual expenditures relative to the cost savings. This study applied integrated building scale cost models to assess the potential economic benefits of more advanced decentralized water reuse frameworks (e.g., reclaimed gray water for shower and laundry, reclaimed gray water for server cooling), with the ultimate aim of providing more economical approaches to increase sustainability and resiliency of buildings at U.S. Army installations. This study developed life cycle cost models of different building water reuse frameworks to characterize associated life cycle costs of systems and benefits in terms of return on investment. In an existing barracks building occupied with 500 personnel, both gray and black water treatment and reuse systems for toilet flushing do not provide economic benefit within system design life of 20 years. Incorporating broader water end uses such as shower and laundry resulted in a financial benefit after 26 years, with greater benefits at higher building occupancies. Also, economically favorable water reuse opportunities exist at Army data centers that require 130 kgal per day for server cooling. By performing sensitivity analysis over a range of key parameters – unit price of water, system capital costs, discount rate, and wastewater recovery percentage – the most important drivers of ROI were identified. In the context of current Army Directive 2020-03 Installation Energy and Water Resiliency Policy, the results support financially viable approaches for implementation of water reuse in military facilities that can also reduce resupply demands in grid-down or other emergency scenarios.

1. Introduction

Department of Defense (DoD) installations used 85.5 billion gallons of potable water in the fiscal year 2016 (FY16). At the same time, installations generated nearly an equivalent amount of sewage and paid for its treatment.1 Besides water demand for vehicle wash rack, irrigation, and dust suppression, potable water is the main type of water used by Army installations, though this level of purity is not required for all applications. Toilet flushing, urinal flushing, faucet use, and showering at Army installations are the largest water end-uses, which account for 25% of the total water...
consumption. Across the U.S. it is estimated that 30% of indoor potable water used within buildings is for toilet flushing alone. Using a “fit for purpose” water management approach has the potential to reduce potable water demand, increase sustainability of existing water supplies, reduce hydraulic load on overloaded sewer systems, and reduce cost for both purchased water and sewage treatment services. In addition, water reuse strategies have the potential to support the achievement of a mandated water conservation target (2% per year potable water demand reduction from 2007 through 2025). support current Army Directive 2020-03 Installation Energy and Water Resiliency Policy (maintain mission critical functions from known vulnerabilities), and support the new water resilience initiatives as part of the DoD climate adaptation plan (including water reuse opportunities at military installations to mitigate climate-driven water supply issues).

A typical DoD building, such as a barracks or office building, uses potable water for all uses, with few cases of buildings that reuse water for landscape irrigation or toilet flushing. Depleting water resources, population growth along with increasing urbanization, and rise in water demand have caused governments and regulating bodies worldwide to develop new ways to conserve scarce water resources. In addition, obtaining reliable sources of water – particularly in military settings – can represent an operational, logistical, and economic burden in water-stressed regions. Some building managers are considering a cascading, fit-for-purpose approach that reserves potable water for necessary uses, leveraging processed gray water and rainwater for other purposes thereby reducing DoD potable water demand and potentially reducing costs. When considering water reuse, decentralized water treatment and reuse systems have the potential to play a significant role in urban settings, U.S. Army fixed installations, and contingency operating bases where serviceable centralized infrastructure is limited due to system aging and deterioration, mobility requirements, or disaster impacts. While on-site water reuse can reduce the building water demand and help maintain mission critical functions in terms of limited water supply, economic, retrofit challenges, stakeholder perception, and regulatory uncertainty can represent barriers to adoption.

More broadly, the implementation of decentralized water reuse may result in other potential (unintended) impacts related to the environment, public health, and infrastructure; however, these were considered outside the scope of this study. Water reuse at the building scale can take several forms depending on the building size and function, regulatory requirements, and water stress risk. Local price of water and the amount of recoverable water are key drivers of payback for building scale water reuse systems. Water reuse is generally regulated at the state level, which is reflected in building plumbing codes. In addition, counties often have specific health related requirements. The use of recycled gray water in buildings is currently allowed at the military site in California. The codes in California contain requirements that govern required treatment level, material, type and location of locking valves, marking, separation/barriers, and signage. Regulatory Framework Title 22 (California) requires inspection by an AWWA cross-connection control program specialist prior to initial operation and annually thereafter. Unfortunately, in water reuse approaches currently allowed by regulators, such as reusing water for toilet flushing, the associated return on investment (ROI) – a key metric for decision-making by the Army stakeholders – is poor in many regions due to the low market price of existing potable water supply and relatively low water demand for toilet flushing alone. While robust treatment technologies can ensure acceptable water quality for end uses, the economic aspects of advancing water reuse at Army installations need to be further investigated to avoid institutional barriers (i.e., funding), given that the Net Zero installation policy requires solution sets that are cost effective (e.g., ROI > 1). In addition, mission critical facilities need – in the case of grid-down or other emergency scenarios – to maintain critical mission functions and maintain installation water security and resilience.

The objectives of this study were (1) to characterize associated life cycle costs of different building water reuse frameworks, including more advanced frameworks with increased potential for return-on-investment; and (2) to determine critical factors driving the suitability of water reuse systems for mission sustainment. The scope of the study included four different building water reuse frameworks (recycled gray water for toilet flushing, reclaimed black water for toilet flushing, reclaimed gray water for shower, laundry, and toilet flushing, reclaimed gray water for server cooling) that were applied to two different building types (Army barracks and Army data centers).

2. Methods

2.1 Development of building water reuse frameworks

In this study, four different building water reuse frameworks were modeled to characterize life cycle costs and determine critical factors driving the decision-making of water reuse systems for mission critical facilities. The building water reuse frameworks included: (1) recycled gray water for toilet flushing; (2) reclaimed black water for toilet flushing; (3) reclaimed gray water for shower and laundry; and (4) reclaimed gray water for server cooling (Fig. 1). Gray water refers to wastewater from drinking fountains, bathroom sinks, laundry, and showers. Black water refers to wastewater from toilets and kitchen sinks with high organics and solids and lower biological stability. Reclaimed water is defined herein as treated wastewater that is fit for a given end use but has not yet been reused (largely discharged into natural bodies of water). Also, recycled water is defined as treated wastewater that has been leveraged for a specific end use (e.g., irrigation, toilet flushing). The general design optimization objectives and constraints of the decentralized water reuse frameworks included maintaining or improving...
safety, maximizing water recovery, minimizing operation and maintenance, minimizing capital cost and payback period, minimizing retrofit time, enabling strategic redundancy and maintaining a fallback position, minimizing energy consumption, integrating efficiently with existing infrastructure, and supporting national economic objectives.

The gray water treatment for nonpotable reuse framework considered gray water collection of gray water from drinking fountains, bathroom sinks, laundry, and showers followed by onsite treatment and reuse for irrigation and toilet flushing.\textsuperscript{23–26} The current framework can be found in several applications including on-site building scale gray water treatment and reuse for toilet flushing and irrigation (Wahaso Water Harvesting Solutions Inc., Hinsdale, IL) and gray water recycling for toilet flushing, spray irrigation, and cooling towers (Ecovie, Miami Beach, FL). The on-site building scale gray water treatment and reuse system for toilet flushing and irrigation uses a number of leading-edge filtration, sterilization, and monitoring processes to produce near-potable quality water. The technology is marketed as being able to eliminate health and aesthetic concerns while meeting regulations in most communities.\textsuperscript{15}

The gray water recycling system for toilet flushing, spray irrigation, and cooling towers uses treatment technology including a pre-filter and membrane bioreactor (biological treatment and ultra-filtration) to meet NSF 350 certified water quality for nonpotable use.\textsuperscript{27} The system can be scaled from 20 000 gpd in commercial or industrial applications down to 50 gpd in residential applications. In a previous study, Ward and colleagues\textsuperscript{11} evaluated the use of multi-barrier treatment approaches (combinations of physical, chemical, and/or biological) to remove a broad range of contaminants present in gray water. The combination of ultrafiltration and biofiltration showed significantly better treatment performance (both in terms of turbidity and chemical oxygen demand removal) than the use of single treatment approach (physical or biological alone). Also, a combination of biofiltration and ultrafiltration reach stable performance within 3 weeks and maintained performance for up to 6 months, both when treating synthetic gray water at bench scale\textsuperscript{11} and when treating municipal wastewater at pilot scale.\textsuperscript{28}

The reclaimed gray water for shower and laundry framework extends the previous framework for additional reuse applications. The proposed gray water treatment technologies (Fig. 1) are capable to treat wastewater from drinking fountains, bathroom sinks, and showers and reuse for toilet flushing as well as shower and laundry. This framework can be found in Gray Water Treatment and Reuse Systems (G-WTRS) developed by U.S. Army Corps of Engineer. The G-WTRS was designed to be robust, efficient, and highly scalable for large contingency operation use. The technology includes an optimized high-efficiency physio-biological pretreatment process to remove organics and particulates, ultrafiltration membranes, high flux low energy reverse osmosis (RO) membranes, and a chlorination system.\textsuperscript{29} While the greatest technical risk associated with the framework stems from the suite of water quality requirements that must be met, this risk can be mitigated with multi-barrier treatment technologies coupled with real-time water quality monitoring. From USEPA Guidelines for Water Reuse\textsuperscript{30} and the USACE Applicable Guidelines for Water Reuse at Army Installations,\textsuperscript{31} the recommended reclaimed water quality limits for restricted urban reuse are 30 mg L\textsuperscript{−1} BOD (biochemical oxygen demand), 5 NTU (turbidity unit), and 200 fecal coliform/100 ml. For unrestricted urban reuse, the recommended limits are 10 mg L\textsuperscript{−1} BOD, 2 NTU, and no detectable fecal coliform/100 ml. These water quality limits are...
requirements are generally consistent with National Sanitation Foundation/American National Standards Institute (NSF/ANSI) Standard 350.

Higher levels of water reuse such as black water treatment and direct potable reuse through advanced treatment technologies (e.g., ozone, UV) could be an option for improving water resupply and payback, though regulatory challenges (including monitoring requirements and challenges associated with decentralized treatment systems) may limit that approach in the near term.

2.2 Army building water demand and water price modeling

Recent Army Water Use Intensity (WUI) research was conducted to characterize water use profile by function and mission type. Existing civilian research on WUI primarily focuses on common civilian buildings like single-family housing, apartment complexes, hospitals, schools, and office buildings. Army installations also have unique facilities designed to support and conduct Army missions and operations. These include barracks, dining facilities, data centers, industrial plants, simulator buildings, and laboratories. From the recent WUI study, barracks and data centers both had particularly high WUI and are designated as mission critical facilities. As such, barracks and data centers were studied to demonstrate the financial viability of decentralized water reuse systems implementation.

**Barracks water demand.** The estimated total water demand in Army barracks buildings is 56.5 gallons per person per day, which is within the range of barracks building water demand from past studies. For a baseline scenario, a barracks building occupied with 500 personnel needs 28 kgal per day of water supply for shower (42%), laundry (19%), and toilet flushing (9%). The assumptions for the major water end uses in the model include 10 min shower per person per day, 2.5 laundry loads per person per week, 1.6 toilet flushing per person per day, and 5.3 urinal flushing per person per day.

**Data centers water demand.** Water reuse is currently practiced at Army installations for cooling tower makeup, vehicle wash racks, and for use in data centers. In the server cooling processes, water consumption accounts for approximately 70% through evaporation and approximately 30% through blowdown. Wastewater generated from Army data center cooling processes often contains salts (e.g., chlorine, sulphates, carbonates), dissolved gases (e.g., oxygen, carbon dioxide), and metal ions (e.g., iron, manganese). When considering the recycle of blowdown to reduce net building water demand for cooling processes, the pollutants get highly concentrated over time and continuous removal is required. These pollutants may cause potential operational challenges stemming from fouling, scale formation, corrosion, and biological growth that may eventually result in decreased cooling efficiency (through interference with heat transfer) and equipment failure. Along with real-time water quality monitoring capabilities, these challenges can be avoided with adequate treatment, potentially including disinfection and the addition of scale inhibitors. In the Army data centers, the building water demand is ranging from 0.25 to 48 gallons per square foot per month based on the historical water metering data. The wide range of WUI for data centers is likely due to the significances of data process levels at two different sites (median is 13 gal ft\(^{-2}\) per month, 75th percentile is 26 gal ft\(^{-2}\) per month). This is equivalent to 26 kgal per day on average water demand for a data center with 49,000 ft\(^2\) building footprint.

**Water price.** Army installation water prices vary depending on the water systems characteristics and missions. According to Army Facilities Management in Army Regulation 420-1 (published by Headquarters Department of the Army), installations are required to report installation-wide energy and water consumptions and unit prices to the Army Energy and Water Reporting System. In FY19, an average water unit price of 50 Army installations across the United States was 6.2 $ per kgal (median is 4.42 $ per kgal, 25th percentile is 1.75 $ per kgal, 75th percentile is 9.06 $ per kgal). For baseline scenarios, 9.06 $ per kgal of water unit price was used. In addition, the range of water unit prices for specific installations located in southern- and western-United States (8.5–12 $ per kgal) were also considered to benchmark the cost effectiveness in terms of break-even return on investment (ROI = 0).

2.3 Life cycle cost modeling

In this study, life cycle of the water reuse system is defined as construction through end of design life (excluding salvage and disposal). Unit costs and key assumptions were based on vendor quotes or data from the literature (Table ESI-1†). All associated costs across the life cycle were converted to present value and compared against the annual cost savings from water consumption offsets to evaluate economic aspects of the decentralized water reuse systems for decision-making. The life cycle cost for each water reuse framework was modeled based on cost elements (Table ESI-1†) such as capital costs, operation and maintenance costs, and energy costs collected from demonstration studies. These cost elements were utilized to develop cost functions (Fig. ESI-1†) at different design flows (0.5–50 kgal per day). Capital cost is a fixed cost which includes system and installation cost. The capital cost of each building water reuse framework was calculated based on composition of treatment trains (e.g., biofilter, membrane bioreactor, ultrafilter, reverse osmosis, chlorine) for design effluent water quality (NSF350 criteria). The operation and maintenance costs are annually incurred costs over the lifetime of the decentralized water reuse systems (i.e., 20 years). The costs of labor, consumables, inspection and performance test, membrane replacement, and cleaning were considered in the model as part of operation and maintenance costs. To maintain the treatment performance over system design life, annualized cost associated with membrane replacement every 10 years was included. For energy cost, energy demand (kW h) for each
building water reuse framework were modeled based on design flow rate. The utility consumptions included aeration for the membrane bioreactor and electricity for pumping (influent, membrane bioreactor backwash, sludge). To determine the economic benefits in terms of ROI or net savings for each building water reuse framework, water cost savings for each building water reuse framework were compared based on Army installations water price obtained from Army Energy and Water Reporting System.40

2.4 Sensitivity and uncertainty analyses

Sensitivity analyses were performed to determine the cost drivers for the building water reuse frameworks. Uncertain parameters (water price, building water demand, capital cost, operation and maintenance cost, membrane replacement period, electricity price, discount rate) were differentiated from baseline values in the life cycle cost model to quantify the output changes from the baseline result (Table ESI-1†). In addition, uncertainty analyses were performed using the probability density functions of uncertain parameters to simulate the water reuse at the mission critical facilities (barracks building and data center) and quantify the variability of economic benefits in terms of return on investment. For each reuse scenario, 1000 runs of Monte Carlo simulation were performed using randomly selected values within the probability density function of each uncertain parameter. Detailed assumptions and

Fig. 2  (Left) Heat maps present ROI for each water reuse scenario at a barracks building. Red = negative ROI. Green = positive ROI. White = break-even (0% ROI). Box plot shows Army installation water unit price in FY19. Boxes extend from 25th to 75th percentiles. Within the boxes, 50th percentiles are marked by a horizontal line and mean values are marked by an “X”. Whiskers extend to the 5th and 95th percentile. (Right) Bar charts show payback periods of water reuse system with different water supply options. (A) Recycled gray water for toilet flushing. (B) Reclaimed black water for toilet flushing. (C) Reclaimed gray water for showering, laundry, and toilet flushing.
calculations under certain conditions are noted in the ESI document.

3. Results and discussion

3.1 Water reuse at an existing barracks building

Cost functions and energy demand models were used to assess three types of decentralized building water reuse systems to determine their ROI over a range of relevant scenarios. The resulting returns on investment for the case of retrofittng an existing barracks building indicated that the ROI varies with use case, building occupancy, and water cost (Fig. 2). Also shown are ROI comparisons between scenarios of piped water supply (baseline) versus emergency water supply scenarios in which water is trucked in tanker. For the baseline scenario, it was assumed that installation water unit price and electricity price are 9.06 $ per kgal (75th percentile from FY19 Army installation water price) and 0.15 $ per kW h, respectively. As a result, both gray and black water treatment and reuse systems for toilet flushing were not providing feasible payback period in baseline scenario with centralized water distribution infrastructure. This is due to the high system capital cost relative to a limited water demand offset by the reuse application. Extending the range of reuse applications to include shower, laundry, and toilet flushing resulted in an improved but modest investment of 26 years through water distribution for the baseline case with existing centralized water supply infrastructure.

Different occupancy numbers and water prices were also studied to examine the break-even of return on investment (ROI = 0) through decentralized water reuse systems (Fig. 2). Within 15 years of system performance period, none of the reuse systems for toilet flushing were cost competitive under current settings. When considering higher potable water price (e.g., >80 $ per kgal), recycled gray water for toilet flushing could provide positive ROIs at lower occupancy number than the baseline. For black water treatment system, the reuse framework has potential to recover more treated water for reuse. Nonetheless, less significant benefit was observed as it required higher levels of treatment to meet the NSF350 standards that led to higher costs (capital, operation, maintenance) than gray water treatment and reuse systems. Therefore, decentralized gray and black water treatment for nonpotable reuse will be potentially suitable in regions where specific conditions (e.g., significant nonpotable water demand, policy) are met.

On the other hand, gray water treatment and reuse systems for shower, laundry, and toilet flushing were economically competitive under current settings when occupancy number was greater than 700 at a barracks building. As expected, the result indicated that larger systems with higher occupancy will likely yield higher net savings. This implies that a larger barracks building or a group of smaller barracks buildings nearby will be suitable for building water reuse, though optimized building planning is needed, which is out of scope for this study. More pronounced differences in economic benefit would be expected at higher water price and occupancy number combined. During emergency operations (i.e., water shortage), for example, implementations of water reuse systems for shower, laundry, and toilet flushing are expected to yield greater net savings as potable water supply price will be much higher for trucked water.

Additional analysis was performed using uncertain parameters to simulate the water reuse opportunities at given conditions. For Army installations located in southern- and western-United States where potable water unit prices are ranged from 8.5 to 12 $ per kgal, gray water treatment and reuse system for shower, laundry, and toilet flushing at an existing barracks building (600 occupancy) provided feasible system payback in 20 years, with the risk of investment loss (ROI < 0) of 53% (Fig. 3). Although there is a higher chance of investment loss revealed under the conditions studied, lower risk of loss with higher ROI are expected at slightly different conditions (e.g., higher water price and/or lower discount rate) based on the result of Spearman’s rank correlation coefficient. The implications are further supported by the cost drivers discussed in section 3.3.

3.2 Water reuse at Army data center

The decentralized gray water treatment and reuse systems have capabilities to remove the pollutants presented throughout the cooling processes and reduce net building water demand. One of the mission critical data centers within Army installations consumes 922 kgal per month on average (0.8% of total water demand) and the mission needs to be sustained even during emergency operations. Another mission critical data center consumes 34 kgal per month on average (0.1% of total water demand). Based on the historical water consumption data for Army data centers, the range of Army data center water demand (0.4 to 78 with median value of 21 kgal per day) were used to evaluate the economic benefits of systems in terms of return on investment. When considering decentralized wastewater treatment and reuse options for server cooling, the result showed possible system implementation opportunities to support mission critical Army data centers (Fig. 4A). Within the Army data center water demand, upper range of WUI (75-95 percentile) could potentially provide positive ROIs within 20 years of system design life under normal operation through main water supplies. Under baseline scenario, capital and annual expenditures for decentralized wastewater treatment system can be returned in 20 years at 90 kgal per day water demand for server cooling. For trucked water scenario as an alternative water supply option during interrupted main water supply, system costs can be returned in 1.4 years with water unit price of 100 $ per kgal. The result implies that implementation of gray water treatment and reuse for Army data server cooling provides benefits, in both economic and resiliency perspectives, given that Net Zero installation policy and Army Directive 2020-03 require
alternative water supplies that are cost effective (e.g., ROI > 1) for mission sustainment.

Under conditions evaluated, net savings of reclaimed gray water for server cooling could potentially be greater in case if local water price and water demand are higher than the baseline. Army data centers have relatively lower water consumption compared to a conventional commercial data center. Furthermore, a hyperscale data center with housing several thousand cloud servers requires significantly higher water demand (0.5–3 Mgal per day) for server cooling. Since Army continues to reduce number of data centers and shifting towards cloud-based systems, future water demand of consolidated data centers for server cooling is expected to be much greater than the historical water demand. From the result of Monte Carlo simulation, greater success measured as risk of investment loss was observed when required water

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*Fig. 3* (Left) ROI uncertainty determined via Monte Carlo simulation and (right) sensitivity across the most significant inputs at given conditions as measured by the Spearman’s rank order correlation coefficients. Among the parameters studied for shower, laundry, and toilet flushing water reuse in a barracks building, water price was the input parameter to which ROI variability was most sensitive ($\rho = 0.88$).

*Fig. 4* (A Left) Heat map presents ROI for server cooling blowdown reuse system at an Army data center for server cooling. Red = negative ROI. Green = positive ROI. White = break-even (0% ROI). Box plots show Army data center water demand and water price for server cooling. Boxes extend from 25th to 75th percentiles. Within the boxes, 50th percentiles are marked by a horizontal line and mean values are marked by an “X”. Whiskers extend to the 5th and 95th percentile. Within the heat map, purple and orange dotted lines represent water demand for conventional commercial data centers. (A Right) Bar chart presents system payback periods under given water supply scenarios. ROI uncertainty via Monte Carlo simulation (B left) and the sensitivity of ROI to key input parameters as characterized by Spearman’s rank order correlation coefficients (B right).
demand for cooling processes are ranged from 100 to 150 kgal per day (Fig. 4B). Under conditions studied, statistically significant correlation between water price and system ROI was revealed from the Spearman’s rank correlation coefficient analysis. The result indicated that water price ($\rho = 0.87$) is the most sensitive input among the parameters studied for the water reuse scenario. Although water recovery rate is expected to be 21% with existing decentralized wastewater treatment technologies relative to the total water demand for server cooling, water reuse at Army data center is still a viable option to reduce net water demand and support resiliency of mission critical facilities during a water supply disruption event.

3.3 Cost drivers

Sensitivity analyses were performed to identify cost drivers of the building water reuse systems (Fig. 5). The uncertain parameters (system capital cost, maintenance cost, membrane replacement period, consumable cost, water and electricity prices, water demand, and discount rate) were differentiated by the uncertain ranges (Table ESI-1†) from the baseline to quantify output sensitivity as measured by change in net savings for each water reuse scenario. As expected, one of the major cost drivers for both gray and black water treatment and reuse systems for toilet flushing was building water demand (occupancy). Increased building water demand did not provide positive change in net savings. Under condition evaluated, this implies that smaller gray and black water treatment and reuse systems for toilet flushing may be suitable in some cases with limited access to water supply, though optimized system design needs to be further investigated from future studies. In addition, system capital cost of gray and black water treatment and reuse systems was another major cost driver for toilet flushing. This indicated that capital cost of the systems is an economic barrier to adopt the technology due to significantly higher capital cost than water savings for the end use. The result is consistent with an on-site gray and black water treatment system for toilet flushing.44

In contrast to water reuse systems for toilet flushing, results from sensitivity analyses showed that the price of water in the region was one of the major cost drivers for shower, laundry, and toilet reuse system in an existing barracks building. A higher unit price of water would result in greater net savings and shorter payback periods. Also, capital cost of water reuse system was a critical factor for technology implementation. This implies that greater net savings are expected along with advancement of decentralized wastewater treatment technologies. Another key driver for the systems was the discount rate. Because the discount rate is correlated with the present value of the future expenditures and savings, lower discount rate (4%)45 from the recommended federal discount rate of 7% (ref. 46) could potentially provide greater net savings than the increase in net savings with lower range of system capital cost. Although building water demand was relatively less sensitive factor than the major cost drivers under conditions studied, it was revealed that increasing the fraction of reuse water to support a wider range of demands (e.g., shower, laundry, toilet) would result in a better net saving, assuming other parameters are held approximately constant. This implies that the system may not be appropriate in some regions where unit water price is low and water reuse opportunities are more restricted.

![Fig. 5](https://example.com/f5.png)

**Fig. 5** Sensitivity analyses of building water reuse systems with upper and lower ranges of uncertain parameters. (A) Gray water treatment and reuse system for toilet flushing. (B) Black water treatment and reuse system for toilet flushing. (C) Gray water treatment and reuse system for shower, laundry, and toilet flushing. (D) Data center water reuse system for server cooling.
Similar to the decentralized wastewater treatment system for shower, laundry, and toilet flushing, the sensitivity result showed that water price, capital cost of system, and discount rate were the principal cost drivers for the blowdown water treatment and reuse system for Army data center cooling (Fig. 5D). This implies that economically favorable water reuse opportunities exist at Army data centers when certain conditions are met. For example, water reuse for server cooling will be suitable for the installations where unit water price is higher than 10 $ per kgal and greater economic benefits are expected during emergency operations requiring alternative water supply options. Decreased capital cost would result in a better net savings with technological advance in decentralized treatment systems. Also, economically feasible water reuse can be achieved with federal discount rate lower than the baseline (6%). Furthermore, higher water demand for server cooling (e.g., >130 kgal per day or >6.5 MW data center47) are expected to provide a greater ROI while other parameters remain constant. Net savings were less sensitive to other uncertain parameters (e.g., maintenance labor cost, electricity price, consumable cost) relative to the principal cost drivers.

4. Conclusions

This study developed life cycle cost models of different water reuse frameworks for the retrofit of mission critical facilities within U.S. Army installations. Based on available case studies at the time of this analysis, the models provide insights for building and infrastructure managers that can inform implementation of economically-viable building water reuse systems. Beyond reducing long-term costs, these systems also have the potential to support climate adaptation and support installation water security and resiliency.

The key conclusions are as follows:

- The economic feasibility of implementing water reuse systems in existing buildings is dependent on the reuse framework and water unit price. For installations where average water unit price is 10 $ per kgal and a barracks building is occupied by 700 personnel, gray water treatment and reuse for shower, laundry, and toilet flushing provided economic benefits in terms of positive ROI, despite their high capital costs. This is due to greater water savings relative to the differences in capital and operational costs.

- Server cooling blowdown reuse will not be economically favorable with current Army water price and water demand for server cooling. To obtain economic benefits, it is recommended to target water reuse systems for Army data centers where average water unit price is ≥10 $ per kgal and water demand for server cooling is ≥130 kgal per day.

- Negative ROIs observed from the baseline results could be reversed under a water disruption event when water supply is limited and alternative water sources are very costly.

Based on these results, the uncertain parameters such as unit water price, system capital costs, discount rate, and wastewater recovery for building water demand need to be considered when evaluating opportunities of water reuse in existing grid-connected buildings. In addition, residual salvage values or disposal costs of the systems may be included in future analyses when more data become available. Although electricity consumption was not a key cost driver in this study, future studies may consider the variance of electricity prices across U.S. cities to capture the range of recurring energy costs of the water reuse systems. Also, future studies could include the potential integration of locally generated, renewable energy (e.g., via solar panels) to reduce energy purchasing requirements and increase resiliency. The economics can change quickly for facilities that must maintain operations and that have to consider periodic reliance on imported water for resupply during emergency operations. Further, new buildings that might require new infrastructure or that may be in off-grid locations would likely have improved ROI through reduction in onsite water supply needs or new distribution pipeline costs. Future studies may also explore opportunities to drive down costs of decentralized water treatment and reuse by grouping facilities to achieve greater economies of scale. More broadly, location-specific implementation of reuse frameworks should consider the broader implications of deploying these systems, working avoid unintended detriments (e.g., increasing contaminant concentrations in sewers due to lower volumes and reduced flow rates), system monitoring and health risks, and impacts on local water distribution systems.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This research was funded by the Assistant Secretary of the Army for Installations, Energy, and Environment.

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