CCC 2025 **Proceedings of the Creative Construction Conference** (2025)
Edited by: Miroslaw J. Skibniewski & Miklós Hajdu & Žiga Turk
https://doi.org/10.22260/CCC2025/0091

INITIAL COST ANALYSIS OF A NEW WASTEWATER TREATMENT APPROACH

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Abstract

Conventional wastewater management systems incur substantial costs due to the uniform treatment of all household effluent, regardless of its contamination level. In typical residential plumbing, greywater (GW) and blackwater (BW) are combined and directed to centralized treatment facilities, where both are processed as high-strength wastewater. This approach overlooks the relatively low pollutant load of GW, which can be treated at lower cost for non-potable reuse. This study proposes a source-separation system that isolates GW at the point of generation and routes it to an in-house recycling unit, thereby reducing the volume of wastewater requiring intensive treatment. A life cycle cost (LCC) analysis, based on NIST standards, reveals potential savings of up to 29% compared to conventional systems, primarily due to decreased treatment loads and reduced BW infrastructure requirements. The results underscore the economic advantages of decentralized, differentiated treatment in residential wastewater management.

Keywords: Economic Analysis, Greywater, Life Cycle Cost Analysis, Sustainability, Water Savings, Wastewater Treatment.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2025.

1. Introduction

Water is one of the planet's most vital resources, yet global demand is projected to increase by 55% by 2050, intensifying shortages and competition[1]. Population growth, urbanization, and climate change have made freshwater supply less predictable and sustainable[2]. As a result, cities are increasingly exploring water reuse strategies, with greywater emerging as a key alternative for non-potable uses like toilet flushing, irrigation, and cleaning[3]. Conventional plumbing systems, however, mix greywater and blackwater into a single stream, requiring intensive treatment typically unnecessary for greywater[4]. In contrast, greywater can be treated and reused with minimal filtration.

This study proposes a novel wastewater management system that separates greywater at the source using residential dual plumbing and decentralized greywater systems. These systems collect, filter, and store greywater for immediate reuse[5]. The proposed system reduces wastewater outflow, lowers sewer pipe diameter requirements, and decreases treatment plant demands, potentially resulting in significant cost savings. However, system installation, operation, and maintenance introduce new costs, necessitating a detailed economic assessment.

The primary goal of this study is to evaluate the life cycle costs (LCC) of implementing this system at an urban scale, using Chicago as a case study. The city's diverse utility rates, consumption patterns, and infrastructure costs make it an ideal test case. The analysis compares conventional and proposed systems based on sewer construction and maintenance costs, treatment flow rates and associated expenses, and annual utility bills.

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Serving as a decision-support tool, this study will educate engineers, urban planners, and policymakers of the cost-efficiency and feasibility of decentralized greywater reuse, offering a sustainable path forward for urban water management.

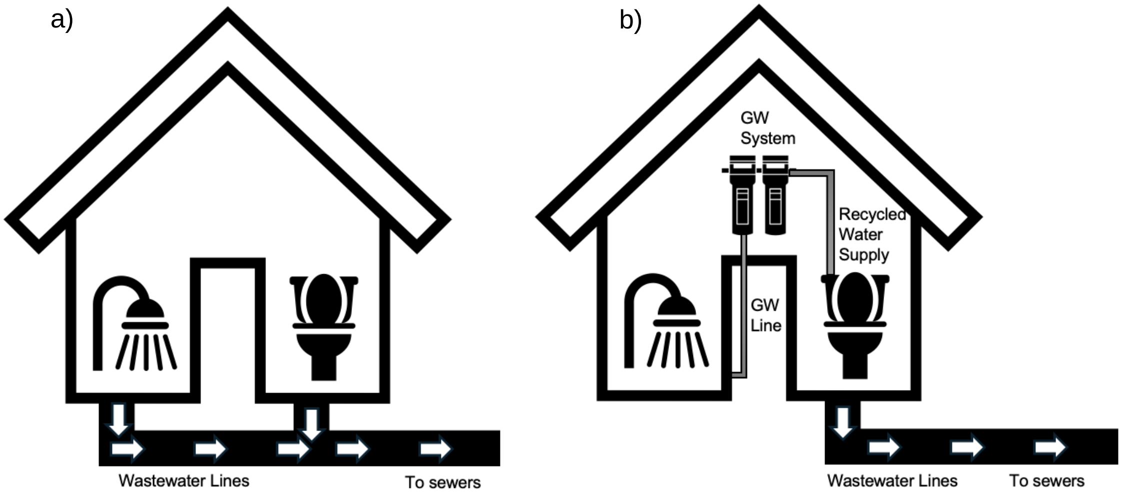

Fig. 1. (a) Conventional Settings; (b) Proposed Settings

2. Literature Review

Sustainable urban wastewater management involves decentralizing infrastructure, matching water quality to usage, harvesting stormwater, and improving resilience through diversified sources[6]. The United Nations' Sustainable Development Goals (SDGs), particularly Goals 6, 11, and 12, emphasize access to clean water, sustainable communities, and climate action[7]. Greywater reuse has gained prominence in this context, as greywater accounts for up to 75% of domestic wastewater[8]. Reusing it reduces freshwater demand, lowers sewage discharge, and decreases treatment costs[9]. Moreover, larger centralized treatment plants can negatively impact the environment, further motivating decentralized reuse strategies. Prior studies have explored various approaches: Kjerstadius et al. (2015) analyzed nutrient recovery in separate streams of blackwater, greywater, and food waste[10]; Dewalkar and Shastri (2020) developed a gravity-based greywater treatment system integrated into high-rise buildings[11]; Walker and Duquette (2022) examined energy recovery from wastewater via turbine systems[12]; and Chen et al. (2022) explored sewage heat utilization through predictive modeling[13].

Greywater reuse has become increasingly important due to urbanization, industrial activity, and growing water scarcity[14], [15]. The WHO identifies greywater as a viable alternative source given its volume, low pathogen load, and non-potable potential[16]. Many regions have adopted greywater reuse technologies and policies: Los Angeles recycles 13–65% of greywater for irrigation, and Brazil saves 29–35% of water via toilet flushing with treated greywater[17]. Informal reuse practices, such as using bathwater for irrigation, have long existed in countries like Australia, Syria, South Africa, Israel, and Jordan[18].

Evaluating the economic feasibility of these systems is essential, and Life Cycle Cost Analysis (LCCA) is the preferred method. LCCA, the economic counterpart to life cycle assessment, evaluates costs over a system's lifespan, including capital, maintenance, energy, and replacement costs, along with assumptions such as discount rates and analysis periods[19], [20], [21]. Widely applied in water and energy projects, LCCA provides outputs using metrics like Net Present Value (NPV), Benefit-Cost Ratio (BCR), Payback Period (PP), and Internal Rate of Return (IRR)[22], [23]. These tools collectively support sound engineering and planning decisions for sustainable wastewater solutions.

3. Methodology

The initial phase of this study involved an extensive review of literature on sustainable development and wastewater management strategies. Given that the economic evaluation is based on Life Cycle Cost Analysis (LCCA), relevant publications on LCCA methodologies were also examined. The 2020 edition of the Life-Cycle Costing Manual for the Federal Energy Management Program (FEMP) by the National Institute of Standards and Technology (NIST)[24] was particularly instrumental in shaping the LCCA model used in this research. Following the literature review, a base case (BC) and an alternative case were established. The base case serves as a benchmark for evaluating the proposed system represented by the alternative case. Once these scenarios were defined, key assessment parameters were identified, primarily focusing on financial indicators such as construction costs, maintenance costs, and utility expenditures. Government sources were consulted to obtain cost indices and escalation rates, while established global databases and tools were utilized to estimate cost structures using relevant equations and procedures derived from the literature.

Fig. 2. Methodology Flow Chart

4. Model Development

The model was developed to incorporate all necessary parameters for evaluating the feasibility of the proposed wastewater management system. These elements were organized into a comprehensive cash flow diagram, as illustrated in Figure 3. Parameters were grouped into key categories, including initial construction costs, timing of expenditures, types and quantities of all relevant payments, and their associated Equivalent Annual Costs (EAC). The analysis covered costs related to the Wastewater Network, Wastewater Treatment Plant (WWTP), Greywater System (GWS), and utility bills.

To support the model, specific datasets were collected for each category: Wastewater Data, Network Infrastructure Data, WWTP Data, GWS Data, and Utility Billing Data. Additional parameters such as time frames, interest rates, and escalation rates were also integrated. To maintain model simplicity and manageability, a number of minor assumptions were applied where appropriate.

5. Data Collection

To assess the feasibility of the proposed wastewater management system, the model was developed to incorporate all necessary parameters and was structured using a comprehensive cash flow diagram. The parameters included initial construction costs, timing, frequency, and categories of all payments related to wastewater infrastructure, utility bills, and greywater systems, as well as their Equivalent Annual Costs (EAC). Key data inputs were gathered across five domains: wastewater flow characteristics, treatment plant data, network specifications, greywater system selection, and associated cost elements.

According to Tchobanoglous et al. (2014), the average residential wastewater generation in the U.S. is 65 gallons per capita per day (GPCD)[25]. Greywater, comprising laundry, bathing, showering, and faucet use, accounts for 43.4 GPCD, or approximately 67% of total residential wastewater, with toilet flushing and dishwashing primarily contributing to blackwater.

Wastewater treatment plant (WWTP) data were modeled using CapdetWorks[26], with adjustments made for region-specific variables such as temperature, land cost, and electricity rates. While the treatment process remained constant across scenarios[27], plant capacity was scaled to match each city’s population. The total wastewater flow for both residential and non-residential sectors was computed using U.S. per capita standards[25], [28], showing a 24.11% reduction under the proposed system due to the diversion of greywater at the household level. This volume reduction increases the concentration of blackwater constituents, necessitating an update of influent parameters in the proposed case model.

The wastewater network was analyzed using the CIGMAT-LCC model[29], incorporating standard U.S. design parameters. Under the proposed system, reduced residential wastewater volume allowed for substantial changes in pipe diameter distribution, especially in street laterals and main lines. For example, 80% of street laterals were adjusted to use 4-inch pipes, the smallest standard size suitable for construction and maintenance, while larger diameters were retained where necessary. Similar adjustments were made to the main lines and trunk sewers, reflecting the expected drop in flow volume and the potential reduction in the number and size of treatment plants.

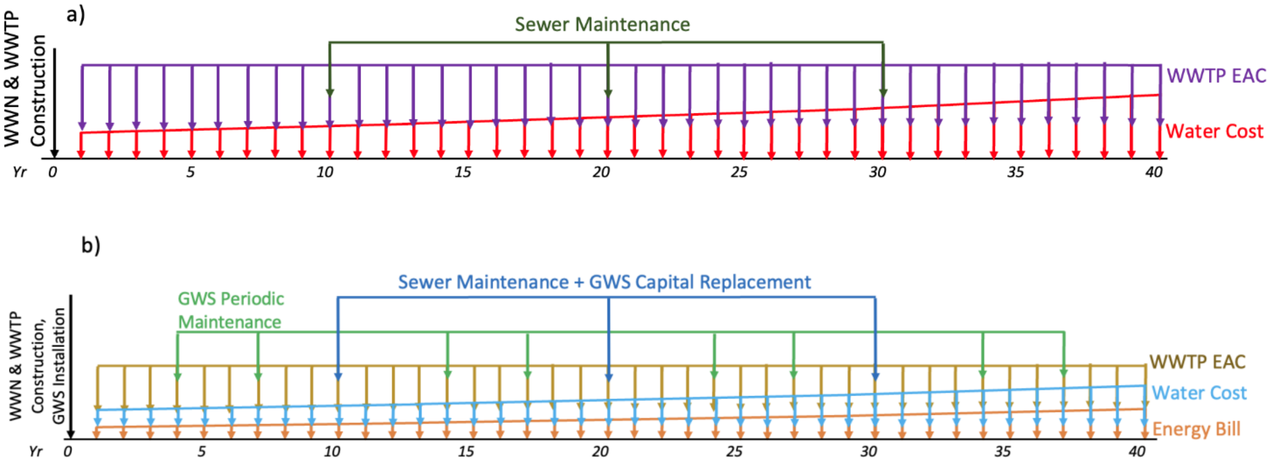

Fig. 3. (a) Cash Flow of Base Case, (b) Cash Flow of Proposed System

For greywater system selection, various products in the U.S. market were reviewed based on functionality, treatment efficiency, and user-friendliness. The Aqua2Use Pro system was selected for its dual-plumbing compatibility, 4-stage internal filtration, 200W automatic submersible pump, 6.8 GPM treatment rate, and 50-gallon storage capacity[30], [31]. This model was assumed to be installed in every residential building to standardize the assessment and simplify comparative analysis.

The main cost components were identified and categorized for both the base and proposed scenarios. The base case includes expenses related to the wastewater network, such as sewer infrastructure and maintenance, wastewater treatment plant (WWTP) construction and operation, and household water utility charges. The proposed scenario introduces additional costs associated with the purchase, installation, maintenance, replacement, and energy consumption of greywater systems. However, these are offset by reductions in conventional infrastructure and operational costs. Specifically, cost-decreasing factors include lower capital and maintenance expenses for street laterals and main sewers, reduced WWTP construction and chemical usage, and decreased residential water bills. In contrast, cost-increasing factors involve the greywater system's capital and lifecycle costs, as well as energy requirements for system operation.

The LCCA used in this framework follows FEMP guidelines[28], applying the nominal discount rate to account for the time value of money. Key time periods include the base date (project start), study period (recommended at 40 years for non-energy systems), and service period (lifetime of individual components) [30].

To maintain clarity and manageability, several assumptions were made. Stormwater runoff and infiltration impacts on sewer costs were excluded. All capital replacements, including for greywater systems with a 10-year lifespan, are assumed to occur at the end of their service life[32]. Greywater systems are considered for residential applications only, excluding commercial and industrial buildings.

6. Life Cycle Cost Analysis

Both cases include specific cost elements, as previously mentioned, which are calculated in this chapter. Before computing the life cycle costs (LCC) for each case, the present worth (PW) of all cost elements was determined.

For Wastewater Network Costs, input values in the CIGMAT-LCC model were adjusted based on the selected cities and cost indices for construction, maintenance, and labor obtained from the RSMeans database. The model assumes pipe maintenance occurs every 10 years, with all costs discounted to present value. The sum of capital and maintenance costs yields the present worth of the wastewater network, denoted as WN_{BC} for the base case and WN_{A} for the proposed system.

For Wastewater Treatment Plant (WWTP) Costs, the determining factors are the number of plants required and the cost per plant for treating wastewater. The required number of plants, N_{TP}, is calculated by multiplying the average per capita wastewater flow by the population and dividing by the plant capacity:

$$N_{TP_{BC,A}} = \frac{(Avg\ WW\ Flow\ per\ Capita) * P}{(Plant\ Capacity)} \tag{1}$$

The total present worth of WWTP costs is then:

$$TP_{BC,A} = (Plant\ Cost)_{BC,A} * N_{TP_{BC,A}} \tag{2}$$

Chicago has its own structure for calculating water and sewage bills, which was obtained from the city of Chicago website[33]. The cost is discounted to present value using the formula:

$$W_{BC,A} = \frac{w_{flat}\left[1-\left(1+{}^{g_w}/_{(1+i)}\right)^n\right]}{i-g_w} + \frac{s_{flat}\left[1-\left(1+{}^{g_s}/_{(1+i)}\right)^n\right]}{i-g_s} \tag{3}$$

where W represents the total water cost, and on the other side w is the Water portion, s is the Sewage portion, i is the nominal discount rate, n is the study period, and g_w, g_s are the expected increase of water and sewage rate every year, respectively.

The life cycle cost (LCC) of the greywater system includes the purchase and installation cost I_{GWS}, post-installation water cost W_A, energy cost E_{GWS}, operation and maintenance costs OMR_{GWS}, and the residual value Res_{GWS}

$$LCC_{GWS_A} = I_{GWS} - Res_{GWS} + W_A + E_{GWS} + OMR_{GWS} \tag{4}$$

The energy cost from the greywater system pump is calculated using the following equation:

$$e_{flat} = Power\ (kW) * \frac{Water\ Amount\ (gal)}{Capacity\ \left(\frac{gal}{h}\right)} * \ energy\ rate\ \left(\frac{\$}{kWh}\right) \tag{5}$$

Which is later discounted using the following equation[28]:

$$E_{GWS} = \frac{e_{flat}\left[1-\left(1+{}^{g_e}/_{(1+i)}\right)^n\right]}{i-g_e} \tag{6}$$

where, g_s is the expected increase of energy rate every year.

Single-payment values such as replacement, maintenance, and residual costs are discounted to present value using[28]:

$$PV = F(1+i)^{-n} \tag{7}$$

Annual costs, such as system maintenance, are discounted using[28]:

$$PV = A[\frac{(1+i)^n-1}{i(1+i)^n}] \tag{8}$$

The life cycle cost (LCC) is the summation of all the present worth values of the respective parameters.

$$LCC_{BC} = WN_{BC} + TP_{BC} + W_{BC} \tag{9}$$

$$LCC_A = WN_A + TP_A + GWS_A \tag{10}$$

7. Results

In completion of the calculation, the life cycle cost for Chicago was $57,885,138,269 for the conventional settings, and $40,860,383,854 for the proposed settings. This represents a cost reduction of approximately 29.4%, highlighting the substantial long-term economic benefits of implementing the proposed system at an urban scale. The savings stem primarily from reduced water consumption, lower treatment plant operational demands, and downsized sewer infrastructure requirements. These findings suggest that the proposed system not only supports sustainable water management but also offers a financially viable solution for future city planning.

8. Discussion and Limitations

This study presents a comprehensive economic assessment model for implementing a sustainable residential wastewater management system focused on greywater reuse. While installing, operating, and maintaining greywater systems introduces upfront costs, these are offset by long-term savings in utility bills, sewage network infrastructure, and treatment plant operations, resulting in savings. However, current utility billing practices limit the system's full potential. Water meters measure all water as if it's fully discharged, ignoring greywater reuse. As a result, residents are overcharged and miss out on savings. Introducing sewage meters could resolve this by billing based on actual discharge, further enhancing cost efficiency. The model has such limitations that, if addressed, could improve accuracy. It assumes a single greywater system design, whereas customization based on household behavior, space constraints, and local water scarcity could yield better outcomes. Additionally, exploring the impact of expanding treatment plant capacity and redesigning wastewater networks could refine the model. While this study focuses on economic outcomes, incorporating environmental life cycle analysis (LCA) and social impact surveys would provide a more holistic view. Despite these limitations, the system reduces reliance on wastewater treatment plants, mitigates environmental harm, and promotes water reuse, easing pressure on natural resources. Considering its economic, environmental, and social benefits, the proposed system meets the criteria for a truly sustainable solution.

9. Conclusion

Greywater is often regarded as waste rather than a valuable resource in urban environments. However, in regions facing water scarcity, policy instruments such as financial incentives and updated building regulations have shown promise in promoting greywater reuse, particularly in residential settings. While local regulations are essential, especially for new construction, successful adoption also depends on public awareness and social acceptance. Without adequate understanding of system benefits, maintenance requirements, and user responsibility, the risk of system rejection remains high. Public education and targeted outreach are therefore critical to maximizing the performance and acceptance of greywater systems. Furthermore, comparative studies of greywater, rainwater, and reclaimed water can help guide better policies and strengthen cities' resilience to challenges like drought and climate change.

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