Drainage Velocity Constraints Limit Greywater Reuse in Building Water Systems: An Integrated One Water Framework with Design Guidelines

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Abstract

This study investigates an often-overlooked constraint on greywater reuse feasibility: drainage self-cleansing velocity requirements. An integrated simulation framework coupling WNTR (potable hydraulics), PySWMM (drainage modeling), and NSGA-II (multi-objective optimization) evaluated 72 building configurations varying in height (3-20 floors), demand intensity (0.3-0.6 L/s per floor), and drain diameter (100-200 mm). Results demonstrate that drainage velocity constraints (≥0.6 m/s), not water availability, impose the binding limit on reuse potential. Buildings with 3-5 floors cannot achieve feasible reuse regardless of pipe diameter due to insufficient baseline velocity. Counter-intuitively, smaller pipes enable greater reuse: 100 mm drains allow 47% reuse at 10 floors versus 0% for 150–200 mm drains at the same height. Only buildings with 7+ floors (100 mm drain) or 20+ floors (150 mm drain) achieve meaningful reuse. These findings yield a key design recommendation: drain sizing should be based on post-reuse flows, not pre-reuse peaks. The resulting guidelines enable practitioners to assess greywater feasibility early in planning before committing to hydraulically infeasible targets.

Keywords: Building water systems, design guidelines, drainage velocity, greywater reuse, multi-objective optimization, one water, and self-cleansing velocity.

Practical Applications

This study provides practitioners with actionable guidelines for greywater system feasibility assessment. The critical first step is verifying that baseline drainage velocity exceeds 0.6 m/s; without this, reuse is infeasible regardless of other design choices. Buildings with 3-5 floors cannot achieve viable reuse with standard pipe sizing. For mid-rise buildings (7+ floors), smaller drainage pipes (100 mm) paradoxically enable greater reuse than larger pipes (150–200 mm) by maintaining adequate velocity at reduced post-reuse flows. The key design principle: *size drains for anticipated post-reuse flows, not pre-reuse peak demands*. For new construction, the recommended sequence is (1) verify velocity feasibility, (2) define reuse targets, (3) size drains, then (4) design the potable system, reversing conventional practice. These findings enable early-stage feasibility screening before committing to hydraulically infeasible targets.

Introduction

Building water systems account for approximately 11-12% of global freshwater withdrawals (Flörke et al., 2013; UNESCO, 2024), with this proportion reaching over 20% in industrialized nations. Sustainable building water systems addressing greywater reuse directly advance Sustainable Development Goal (SDG) Target 6.3 goals to significantly increase water recycling and safe reuse (United Nations, 2024), with potential to reduce potable water demand by 28-42% in multi-story buildings (Ghisi & Ferreira, 2007). With approximately 43.9 million multifamily residences in the United States representing 31.4% of housing stock (NAHB, 2019), and mid-rise buildings (5+ stories) comprising the most economically viable candidates for greywater systems (Friedler & Hadari, 2006), the "One Water" integrated management approach offers substantial potential for sustainable urban water governance (US Water Alliance, 2016). However, feasibility assessments typically focus on water savings potential while overlooking critical infrastructure/physical constraints that may limit practical implementation.

Existing greywater reuse research predominantly examines water savings potential, treatment technologies, and economic feasibility. Studies have investigated collection strategies and network optimization (Khor et al., 2020), treatment efficacy using filtration, biofiltration, and disinfection technologies (Bakheet et al., 2020; Filho et al., 2018), and cost-benefit analyses for multi-story buildings (Friedler & Hadari, 2006). These analyses typically evaluate reuse rates by matching greywater sources (showers, sinks, laundry) with end uses (toilet flushing, irrigation), with Penn and colleagues demonstrating that light greywater reuse reduces daily wastewater flows by 25-40% (Penn et al., 2012).

Recent studies have applied multi-objective optimization to greywater systems at household and community scales (Brock et al., 2012; Khor et al., 2020) and explored energy recovery from gravity-driven greywater flow in tall buildings (Hadad et al., 2022; Oron et al., 2024). However, these studies consistently assume hydraulic feasibility without verification, treating potable supply and drainage systems as independent components. While this approach identifies theoretical savings, *it overlooks critical drainage hydraulic constraints that may render proposed systems impractical or require significant infrastructure modifications.*

Building water system optimization has advanced significantly in pump scheduling and energy efficiency. Variable-frequency drive (VFD) pumps enable demand-responsive operation, with studies reporting 40-80% energy savings compared to constant-speed operation (de Souza et al., 2021). Multi-objective optimization frameworks using genetic algorithms have been applied to integrated water systems, including rainwater and greywater reuse (Brock et al., 2012) and green-grey stormwater infrastructure (Leng et al., 2021), demonstrating trade-offs between energy consumption, cost, and hydraulic performance (Gungor Demirci et al., 2020; Sabzkouhi et al., 2022). Zhang et al. developed the SUWStor optimization model for urban wastewater systems incorporating decentralized greywater reuse, generating Pareto solutions that include hydraulic parameters of sewer and reclaimed water networks (Zhang et al., 2023). However, these studies focus on energy and cost optimization without explicitly constraining drainage velocity for self-cleansing requirements. The integration of supply-side pump optimization with drainage velocity constraints in building-scale systems remains unexplored, despite the fundamental coupling introduced by greywater collection and reuse.

Drainage system design follows established plumbing codes requiring minimum self-cleansing velocity (typically ≥ 0.6 m/s) to prevent sediment deposition and pipe blockage (Bailey et al., 2019; Dev et al., 2021). Dev et al. (2021) incorporated this 0.6 m/s velocity constraint into their optimization model for wastewater reuse systems, noting that reduced flow rates from greywater reuse increase the operational cost of flushing when pipes fall below this threshold. Bailey et al. (2019) predicted that water conservation scenarios cause flow velocity at peak discharge to drop below the self-cleaning velocity, indicating potential blockage problems. Conventional practices size drainpipes for pre-reuse peak flows with safety margins but provide no guidance for post-reuse reduced flows. The hydraulic performance of partially filled pipes depends on both flow rate and pipe diameter through Manning's equation (Gupta, 2017), creating non-intuitive relationships between drainpipe sizing and flow velocity. Parkinson et al. developed models showing that water conservation technologies, including greywater reuse, reduce in-sewer flow velocities and increase sedimentation risk (Parkinson et al., 2005). Despite the fundamental importance of maintaining adequate drainage velocity, this constraint remains largely absent from building-scale greywater feasibility assessments and design guidelines.

Previous studies have examined greywater reuse impacts on municipal sewer systems, demonstrating that reuse reduces wastewater flow and velocity. Penn et al. developed a multi-objective optimization model for municipal sewers that constrained momentary wastewater velocity to maintain solids movement, finding that lower velocities from greywater reuse increase sedimentation (Penn, Friedler, et al., 2013). Their companion modeling study (Penn, Schütze, et al., 2013) quantified that greywater reuse decreases sewer flow, velocity, and proportional depth mainly during peak times, while their follow-up study showed that velocity reduction impairs gross solids transport in sewers (Penn et al., 2014). Chowdhury and Rajput found that 100% greywater capture and reuse reduces design flow in downstream sewers, though their hydraulic modeling focused on distribution network impacts rather than drainage constraints (Chowdhury & Rajput, 2016).

Critically, these analyses focus on district-scale municipal sewers rather than building-scale premise plumbing and treat drainage velocity reduction as a consequence to be managed rather than a constraint on feasible reuse rates. *No studies have systematically quantified how drainage velocity requirements limit maximum achievable greywater reuse at the building scale or integrated these constraints into multi-objective optimization frameworks coupling potable supply and drainage systems.* Furthermore, the counter-intuitive effects of drainpipe sizing on feasible reuse rates, where smaller pipes may enable higher reuse in certain configurations due to velocity-flow-diameter relationships, have never been quantified or translated into practical design guidelines for practitioners.

This study addresses these gaps through three objectives: (1) develop an integrated simulation framework coupling potable water supply (WNTR) and drainage hydraulics (PySWMM) under multi-objective optimization (NSGA-II); (2) quantify maximum feasible greywater reuse rates under drainage velocity constraints for 72 building configurations varying in height (3-20 floors), demand intensity (0.3-0.6 L/s per floor), and drain diameter (100-200 mm); and (3) derive parametric design guidelines enabling practitioners to assess feasibility early in planning and navigate trade-offs between water reuse and drainage performance. The framework simultaneously optimizes pump scheduling for energy efficiency and greywater reuse for water conservation, while enforcing minimum pressure (≥ 140 kPa) and minimum drainage velocity (≥ 0.6 m/s) constraints.

The study's scope and limitations include focusing exclusively on cold water systems and employing a steady-state hydraulic analysis on single building configurations. Hot water system optimization is designated as future work; domestic hot water heating represents approximately 15-18% of total residential energy consumption, and dominates water-related energy use in buildings since pumping energy (0.2-0.5 kWh/m³) is an order of magnitude lower than heating energy (~30-50 kWh/m³ for a 50°C temperature rise) (Alfredo et al., 2025; EIA, 2018; Lee et al., 2023). Similarly, hydraulic transients/water hammer, an important phenomenon in premise plumbing systems (Lee et al., 2012), and district-scale interactions are beyond the current scope. The analysis employs a 5-story urban residential building as the base case, with parametric extensions to diverse configurations representative of typical urban residential stock.

The contribution is threefold. First, this study presents the first integrated framework coupling potable supply and drainage systems at the building scale under “One Water” framework, enabling holistic assessment of greywater reuse feasibility constrained by both supply-side energy optimization and drainage-side velocity requirements. Second, parametric analysis reveals counter-intuitive relationships between drain sizing and reuse potential, specifically, that smaller drainage pipes enable higher greywater reuse rates in mid-rise buildings by maintaining adequate velocity at reduced flows, challenging conventional design assumptions that favor oversizing for safety margins. Third, the resulting design guidelines spanning 72 configurations provide practitioners with evidence-based tools for early feasibility assessment, eliminating the current reliance on trial-and-error or simple water balance calculations that ignore drainage hydraulics. These contributions advance both the scientific understanding of coupled building water systems and the practical implementation of sustainable water reuse in the built environment.

Methodology

Base Case Configuration. A 5-story urban residential building serves as the base case (Figure 1). Key parameters include: 15 m total height (3 m per floor), 0.4 L/s base demand per floor with peak factor of 1.6, VFD booster pump supplied by city main at 30 m pressure head, and 150 mm main drain with 2% slope (Table 1). The system collects greywater from sinks, showers, and laundry (65% of total water demand) for reuse in toilet flushing (25% of demand), with the remaining 10% reserved for potable-only uses (*e.g.*, drinking, cooking). Of total water supply, 85% enters the drainage system as wastewater; the remaining 15% accounts for consumptive uses and evaporative losses. The demand pattern exhibits characteristic residential peaks in the morning (6-9 AM) and evening (5-8 PM) periods.

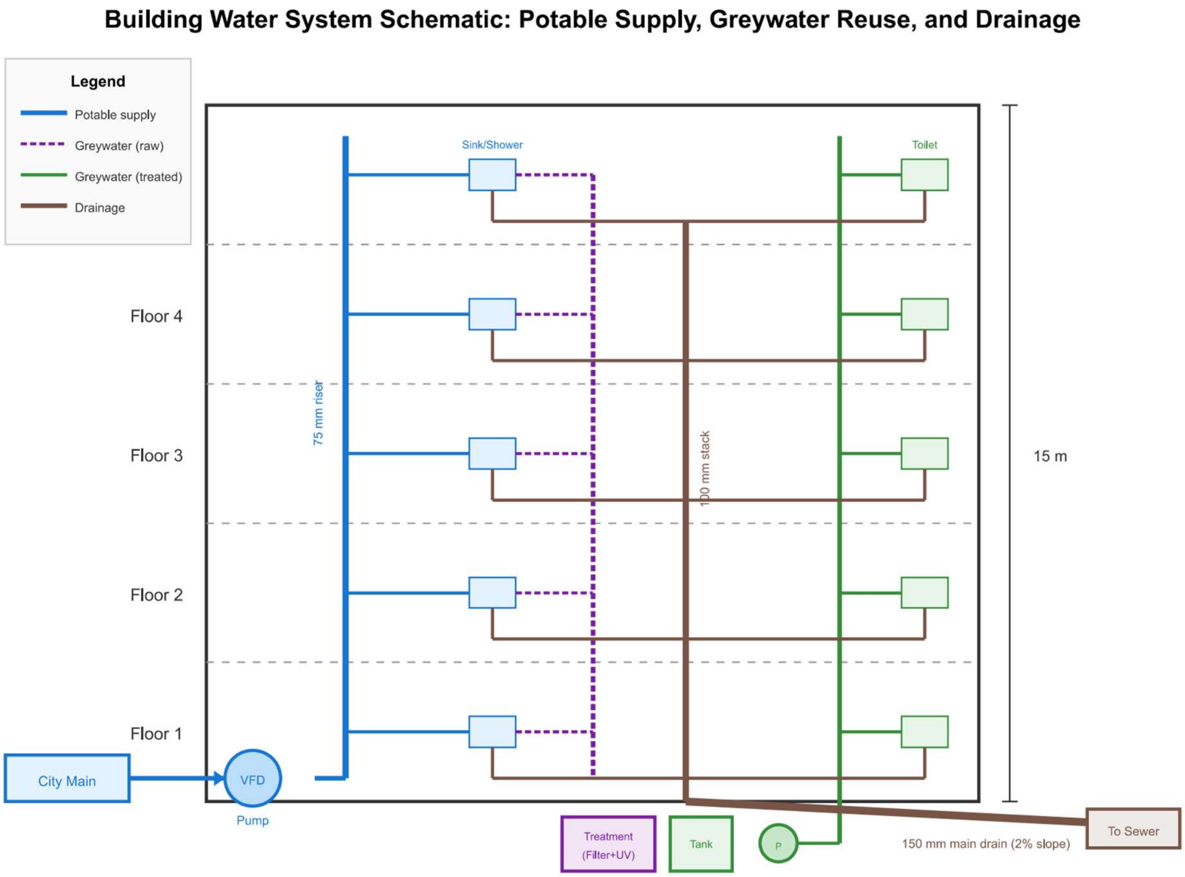

Figure 1. Schematic of the integrated building water system showing potable water supply (blue), greywater collection and reuse (purple/green), and drainage (brown). The 5-story residential building includes a VFD booster pump for potable supply, on-site greywater treatment (filtration and UV disinfection) with storage tank, and a combined drainage system. Greywater is collected from sinks, showers, and laundry (65% of total demand) and reused for toilet flushing (25% of demand). Main drain diameter is 150 mm with 2% slope.

Table 1. Key Building System Parameters (5-story base case)

Parameter	Value	Unit
Building Configuration		
Floors / Height	5 / 15	floors / m
Base demand per floor	0.4	L/s
Peak demand factor	1.6	-
Potable Supply		
City main pressure	30	m

Booster pump (VFD)	0-5 L/s, 18-45 m	-
Riser / Branch diameter	75 / 65	mm
Greywater System		
Collection sources	Sinks, showers, laundry	-
Greywater fraction	65	%
Reuse target (toilets)	25	%
Treatment energy	0.3	kWh/m³
Distribution pump energy	0.2	kWh/m³
Drainage		
Main drain diameter	150	mm
Pipe slope	2	%
Manning's n	0.013	-
Wastewater fraction	85	%
Constraints		
Minimum pressure (top floor)	140	kPa
Minimum drainage velocity	0.6	m/s

Integrated Simulation Framework. The optimization framework couples three computational engines (Figure 2): WNTR for potable water hydraulics (EPANET solver), PySWMM for drainage simulation (SWMM solver), and Pymoo for NSGA-II, multi-objective optimization.

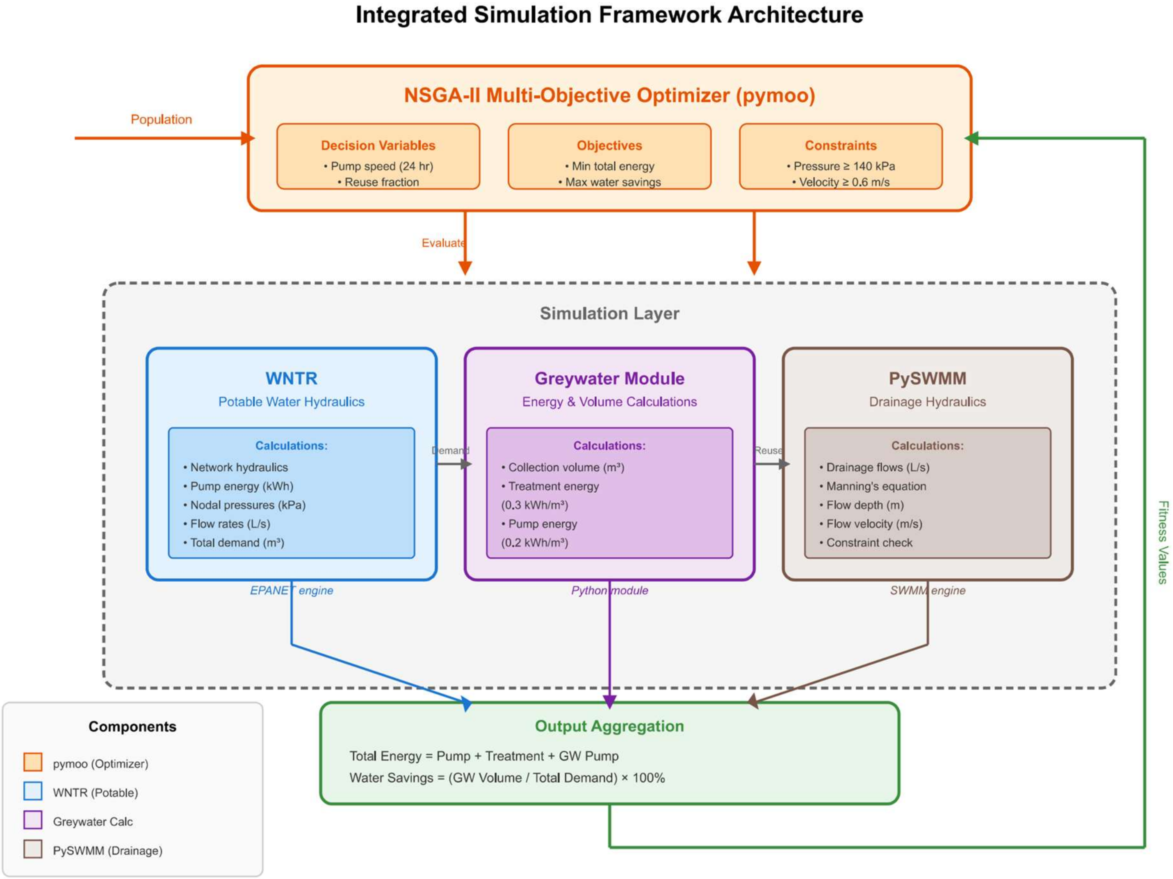

Figure 2. Integrated simulation framework architecture showing the coupling between NSGA-II multi-objective optimizer (pymoo), potable water hydraulic simulator (WNTR/EPANET), greywater energy calculations, and drainage hydraulic simulator (PySWMM/SWMM). Decision variables (pump speed schedule and greywater reuse fraction) are evaluated through the simulation layer, which calculates pump energy, treatment energy, pressures, and drainage velocities. Outputs are aggregated to compute objectives (total energy, water savings) and constraints (minimum pressure, minimum velocity) returned to the optimizer for fitness evaluation. The framework enables simultaneous optimization of potable supply and drainage performance under "One Water" framework in building water systems.

For each candidate solution, WNTR calculates pump energy and nodal pressures over 24 hours using 15-minute timesteps. The greywater module computes treatment energy

(0.3 kWh/m³) and distribution pump energy (0.2 kWh/m³)[1] based on collected volume and reuse fraction. PySWMM calculates drainage velocities using Manning's equation for partially filled pipes with reduced wastewater flow after greywater collection. The framework evaluates two objectives (minimize total energy, maximize water savings) and two constraints (minimum pressure ≥ 140 kPa, minimum velocity ≥ 0.6 m/s).

Multi-Objective Optimization. NSGA-II optimizes 25 decision variables: 24 hourly pump speed values (50-100% of rated capacity) and the greywater reuse fraction (0-80%). The reuse fraction represents the proportion of available greywater (65% of demand) collected, treated, and reused for toilet flushing. The dual objectives minimize total system energy (pumping + treatment + distribution) and maximize water savings. Constraints ensure minimum top-floor pressure of 140 kPa (plumbing code) and minimum drainage velocity of 0.6 m/s (self-cleansing requirement). The optimizer explores the full range of reuse fractions; the velocity constraint determines the maximum feasible value by penalizing solutions where reduced drainage flow falls below the self-cleansing threshold. NSGA-II with population size 50 runs for 60 generations using Simulated Binary Crossover (probability 0.9, η_c = 15) and Polynomial Mutation (η_m = 20) as genetic operators (Deb et al., 2002).

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[1] Treatment energy represents filtration and UV disinfection (literature range: 0.2-0.8 kWh/m³ for non-membrane systems; Bakheet et al., 2020; Friedler & Hadari, 2006). Distribution energy accounts for pumping treated greywater to toilet risers (literature range: 0.05-0.32 kWh/m³ for building distribution; De Souza et al., 2021).

Water Balance Calculations. Daily water demand was calculated from WNTR simulation results aggregated over the 24-hour period, incorporating the hourly demand pattern. Greywater collection volume was computed as daily demand × greywater fraction (0.65) × reuse fraction, representing the portion of sink, shower, and laundry wastewater diverted for treatment. Water savings were calculated as the ratio of reused greywater volume to baseline daily demand, expressed as a percentage. Energy for greywater treatment (0.3 kWh/m³) and distribution pumping (0.2 kWh/m³) was computed based on the collected volume and added to potable pump energy for total system energy.

Parametric Study Design. The parametric study extends across 72 configurations (Table 2): 6 floor heights (3, 5, 7, 10, 15, 20), 4 demand intensities (0.3, 0.4, 0.5, 0.6 L/s per floor), and 3 drain diameters (100, 150, 200 mm). This design spans building heights from 9-60 m and total demands from 0.9-12 L/s, covering low-rise to high-rise residential buildings at varying occupancy densities. All other parameters remain constant per the base case. Output metrics include maximum feasible reuse rate (limited by velocity constraint), total water savings, and final drainage velocity.

The parametric analysis focuses on drainage velocity constraints, which determines maximum feasible reuse rates independent of potable supply system design. For each configuration, baseline drainage velocity was calculated using Manning's equation for partially-filled pipes, and maximum feasible reuse was determined through binary search to find the highest reuse fraction maintaining velocity ≥ 0.6 m/s. Pump sizing and energy optimization, demonstrated for the base case, would be performed subsequently for configurations identified as hydraulically feasible; the parametric results thus represent an upper bound on reuse potential before supply-side constraints are considered.

Table 2. Parametric study parameter ranges

Parameter	Values	Rationale
Floors	3, 5, 7, 10, 15, 20	Low-rise to high-rise residential
Demand per floor (L/s)	0.3, 0.4, 0.5, 0.6	Low to high occupancy density
Main drain diameter (mm)	100, 150, 200	Standard commercial pipe sizes
Total configurations	**72**	6 × 4 × 3 combinations

Notes: Building heights: 9-60 m; Total demands: 0.9-12 L/s (peak: 1.4-19.2 L/s); All other parameters held constant per Table 1. Parametric analysis evaluates drainage constraints only; pump energy optimization applies to the 5-story base case (Table 3).

Results and Discussion

Baseline System Performance. The baseline system consumed 21.5 kWh/day for pumping while maintaining top-floor pressure at 474.9 kPa (exceeding the 140 kPa requirement) and drainage velocity at 0.62 m/s (marginally above the 0.6 m/s threshold). The constant 100% pump speed operation indicates significant oversizing (Table 3).

Table 3. Optimization results comparison (baseline vs optimized)

System Performance: Baseline vs Optimized				
Metric	**Baseline**	**Pump Optimized**	**With Greywater (Balanced)**	**Unit**
Energy				
Pump energy	21.5	3.5	3.4	kWh/day
Greywater treatment	0	0	1.5	kWh/day
Greywater distribution	0	0	1.0	kWh/day
Total energy	**21.5**	**3.5**	**6**	kWh/day
Energy change	-	-83.70%	-72.10%	%
Pressure				
Minimum at Floor 5	474.9	155.1	158.3	kPa
Constraint (≥140 kPa)	Meet constraint	Meet constraint	Meet constraint	-
Water				
Potable demand	100	100	98.6	%

Greywater reuse	0	0	5.6	%
Water savings	0	0	2.9	%
Drainage				
Minimum velocity	0.62	0.62	0.61	m/s
Constraint (≥0.6 m/s)	Meet constraint	Meet constraint	Meet constraint	-

Pareto Front Key Solutions

Solution	Total Energy (kWh/day)	Water Savings (%)	Greywater Reuse (%)	Min Velocity (m/s)
Baseline	21.5	0	0	0.62
Min Energy	3.5	0	0	0.62
Max Savings	8.5	5.7	11.3	0.6
Balanced	6	2.9	5.6	0.61

Constraint Analysis

Constraint	Threshold	Baseline	At Max Reuse (11.3%)	Status
Pressure	≥ 140 kPa	474.9 kPa	156.8 kPa	Satisfied
Velocity	≥ 0.6 m/s	0.62 m/s	0.60 m/s	Binding

Notes: Building configuration: 5 floors, 0.4 L/s per floor, 150 mm main drain

Pump Scheduling Optimization. Pump scheduling optimization alone achieved 83.7% energy reduction, decreasing consumption from 21.5 to 3.5 kWh/day while maintaining minimum pressure at 155.1 kPa (Figure 3, Table 3). The optimal schedule varies pump speed from 50% during nighttime low-demand periods to 98% during evening peaks (Figure 4). This demand-responsive operation tracks the residential water use pattern with morning (6-9 AM) and evening (5-8 PM) peaks. The pump schedule remains largely independent of greywater reuse fraction, indicating that energy savings derive primarily from eliminating oversizing rather than from greywater implementation.

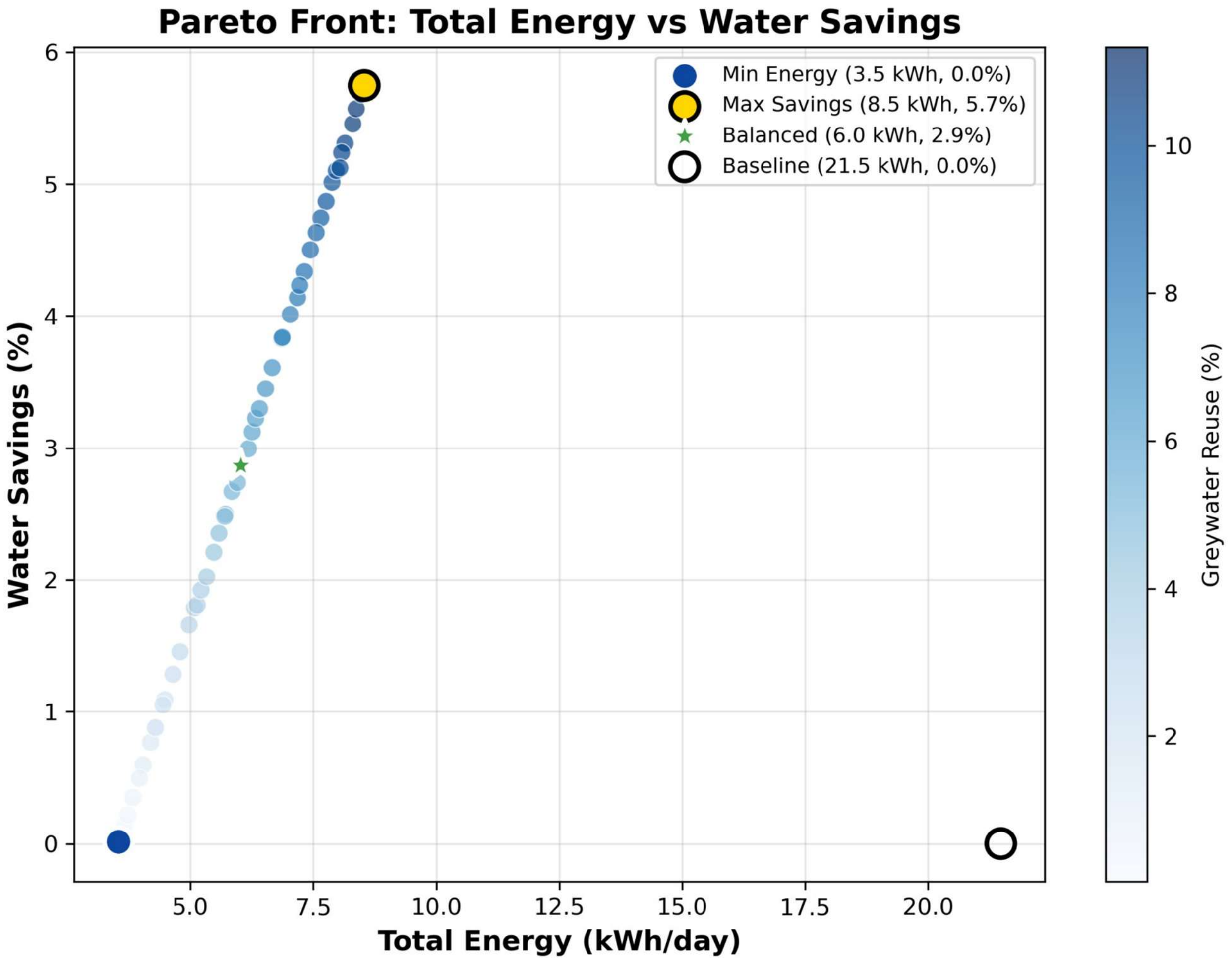

Figure 3. Pareto front showing the trade-off between total energy consumption and water savings for the 5-story residential building with 150 mm main drain. The baseline system (21.5 kWh/day, 0% savings) operates with constant pump speed and no greywater reuse. The minimum energy solution (3.5 kWh/day) achieves 83.7% energy reduction through pump scheduling optimization alone without greywater reuse. The maximum savings solution (8.5 kWh/day, 5.7% water savings) is limited by the drainage velocity constraint (≥ 0.6 m/s) at 11.3% greywater reuse. The balanced solution (6.0 kWh/day, 2.9% savings) represents a compromise between energy efficiency and water conservation.

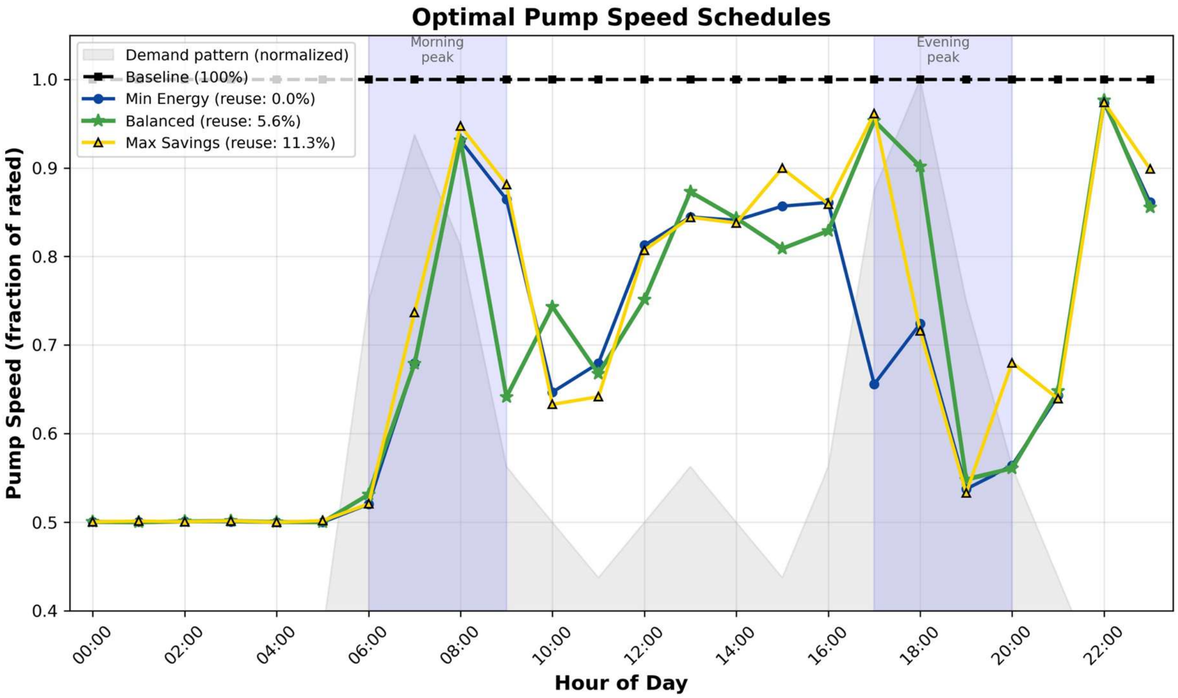

Figure 4. Comparison of optimal pump speed schedules for the 5-story residential building. The baseline operates at constant 100% speed throughout the day. The optimized schedules vary pump speed between 50-100% to match the residential demand pattern (gray shading), reducing speed during low-demand periods (nighttime) and increasing during morning (6-9 AM) and evening (5-8 PM) peaks. The minimum energy schedule (0% reuse) and balanced schedule (5.6% reuse) show similar patterns, indicating that pump scheduling optimization is generally independent of greywater reuse fraction. All optimized schedules maintain minimum pressure above 140 kPa at the top floor throughout the 24-hour period.

Greywater Reuse Optimization. The Pareto front reveals competing objectives between energy consumption and water savings (Figure 3). Three key solutions emerged: (1) minimum energy (3.5 kWh/day, 0% water savings) represents optimized pumping without greywater; (2) maximum savings (8.5 kWh/day, 5.7% water savings) achieves 11.3% greywater reuse; and (3) balanced solution (6.0 kWh/day, 2.9% water savings) provides moderate performance on both objectives.

The drainage velocity constraint becomes binding at 11.3% greywater reuse, limiting maximum water savings to 5.7%. At this threshold, drainage velocity drops to exactly 0.6 m/s, which is the minimum required for self-cleansing. Further reuse would violate this constraint and risk sediment deposition. Greywater treatment and distribution require an additional 2.5 kWh/day (1.5 + 1.0 kWh/day), resulting in higher total energy than pump optimization alone.

Annual projections indicate energy consumption of 2,190 kWh/yr for the balanced greywater scenario, with energy savings of 5,658 kWh/yr and CO_2 reduction of 2,263 kg/yr compared to baseline (Table 4). Water savings reach 1,058 L/yr. Key findings are summarized in Table 4, showing that the binding constraint is drainage velocity rather than pressure, limiting maximum feasible greywater reuse to 11.3%.

Table 4. Annual projections and key findings

Annual Projections				
Metric	**Baseline**	**Pump Optimized**	**With Greywater**	**Unit**
Annual energy	7,848	1,278	2,190	kWh/yr
Energy savings	-	6,570	5,658	kWh/yr
CO_2 reduction*	-	2,628	2,263	kg/yr
Water savings	-	0	1,058	L/yr

*Assuming 0.4 kg CO_2/kWh grid electricity

Key Findings		
Finding	**Value**	**Implication**
Max energy reduction (pump only)	83.70%	Baseline pump oversized
Max feasible greywater reuse	11.30%	Limited by velocity constraint
Max water savings	5.70%	Modest due to drainage limitation
Binding constraint	Velocity	Drainage limits reuse, not pressure

Parametric study results

The parametric analysis across 72 building configurations (varying floors, demand, and drain diameter) reveals systematic relationships between building characteristics and greywater feasibility (Figure 5, Table 5).

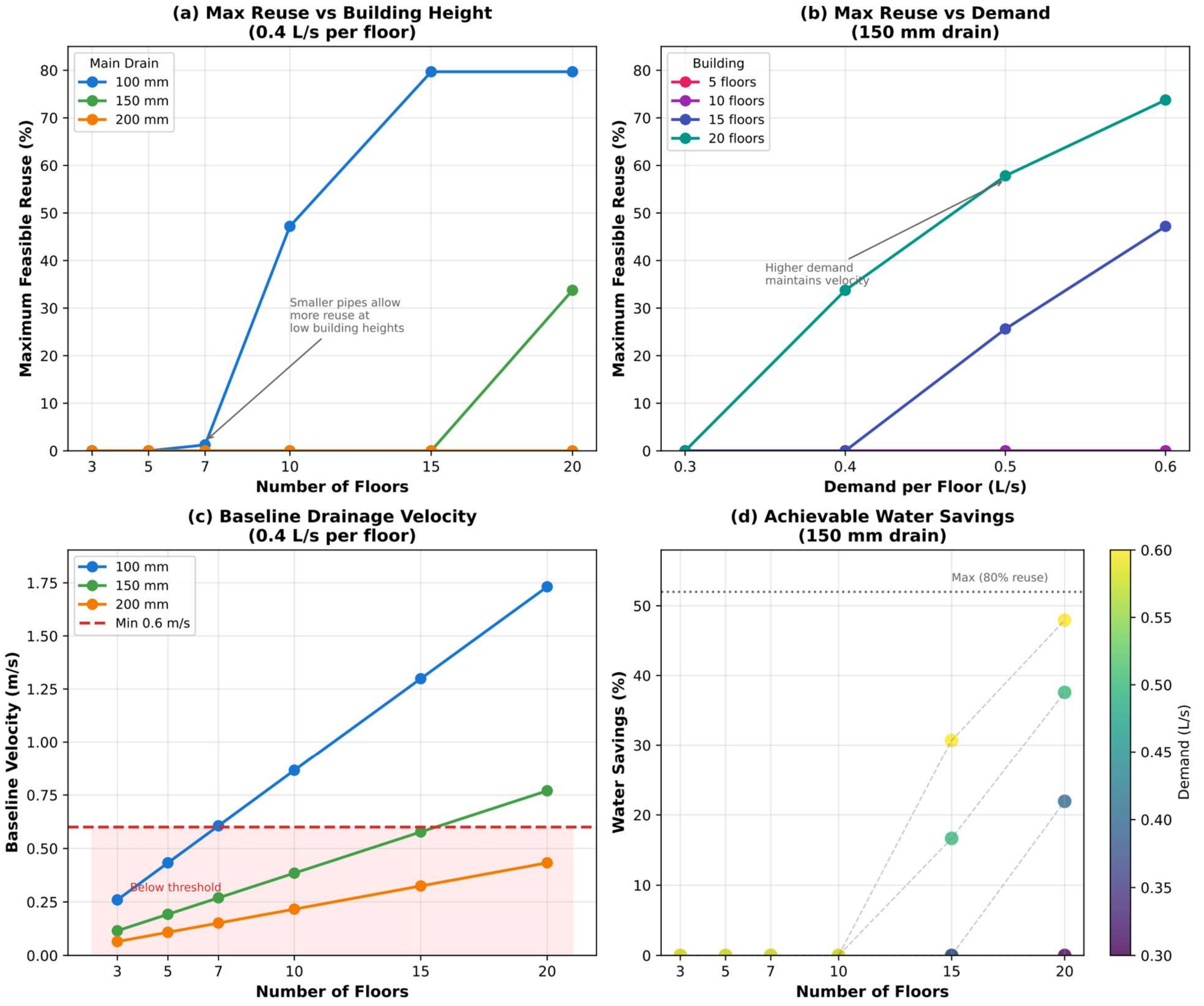

Figure 5. Parametric study results for greywater reuse feasibility across 72 building configurations. (a) Maximum feasible reuse versus building height for three drain diameters at 0.4 L/s demand per floor, showing that smaller pipes allow greater reuse in mid-rise (7-15 floors) buildings. (b) Maximum feasible reuse versus demand intensity for 150 mm drain, showing that higher demand enables greater reuse by maintaining drainage velocity. (c) Baseline drainage velocity (without reuse) versus building height, with shaded region indicating velocities below the 0.6 m/s self-cleansing threshold. (d) Achievable water savings versus building height for 150 mm drain, colored by demand

intensity. Results demonstrate that building height, demand, and drain sizing interact to determine greywater reuse feasibility.

Counter-intuitive pipe sizing effect. The most significant finding is that drainage velocity constraints severely limit greywater reuse feasibility, particularly in low-rise buildings. For 3-5 story buildings at 0.4 L/s per floor, no drain configuration permits feasible reuse, where baseline velocities fall below the 0.6 m/s threshold before any greywater collection begins. At 10 floors, the 100 mm drain permits 47% reuse while 150 mm and 200 mm drains still cannot support any reuse due to insufficient velocity (Figure 5a). This demonstrates the pipe sizing paradox: *smaller pipes maintain the required self-cleansing velocity at lower absolute flow rates, but total building flow must first exceed a minimum threshold.* The conventional practice of oversizing drainage pipes prevents greywater reuse in most building configurations. Velocity in a partially full pipe equals flow rate divided by cross-sectional area. Reducing pipe diameter decreases the flow area, thereby maintaining adequate velocity despite reduced flow after greywater collection. This challenges the conventional practice of oversizing drainage pipes and demonstrates that drain sizing should be based on post-reuse flow rates, not pre-reuse peak flows (Table 5(a)).

Building height effect. Taller buildings support greater greywater reuse because total flow increases with height (Figure 5a). However, the relationship is highly dependent on drain diameter: only 100 mm drains reach meaningful reuse (47-80%) at 10-20 floors, while 150 mm drains first become viable only at 20 floors (34% reuse), and 200 mm drains never achieve feasible reuse up to 20 floors. This dramatically narrows the practical application of greywater systems compared to previous estimates that ignored drainage constraints.

Demand intensity effect. Higher water demand per floor can enable greater reuse by increasing drainage velocity; however, for typical residential demand (0.4 L/s per floor), 5-story buildings with 150 mm drains cannot achieve any feasible reuse regardless of demand intensity. Meaningful reuse requires taller buildings (15-20+ floors for 150 mm drains) (Figure 5(b)).

Baseline velocity as predictor. Buildings with baseline drainage velocity near the 0.6 m/s threshold have limited greywater reuse potential (Figure 5c). The 100 mm drain maintains higher baseline velocity (0.66-1.06 m/s) than 200 mm (0.60-1.05 m/s) at equivalent flows, creating more headroom for reuse in mid-sized buildings. This relationship inverts the typical assumption that larger pipes provide better performance.

Achievable water savings. Water savings are proportional to feasible reuse rate. However, achievable savings are severely constrained by drainage velocity requirements. At 0.5 L/s per floor with 150 mm drains: 3-7 floor buildings achieve 0% savings, 10 floors achieve <1%, 15 floors achieve 17%, and 20 floors achieve 38% (Figure 5d). Buildings with 200 mm drains cannot achieve any water savings through greywater reuse up to 20 floors (Figure 5c, Table 5(b)). These results are substantially more restrictive than previous studies that assumed hydraulic feasibility without numerical verification (Table 5(c)).

Table 5. Greywater Reuse Feasibility by Building Configuration

(a) PIPE SIZING PARADOX

Key Finding	Smaller drains enable more reuse, but only in mid-rise and taller buildings (7+ floors)
Physical Reason	Smaller pipes maintain self-cleansing velocity (≥0.6 m/s) at lower flows; however, low-rise buildings have insufficient total flow to reach threshold velocity
Design Implication	Size drains for post-reuse flow, not pre-reuse peak; verify that baseline velocity exceeds 0.6 m/s before planning greywater reuse.
Example (0.4 L/s/floor)	At 10 floors: 100 mm = 47% reuse; 150 mm = 0% reuse; 200 mm = 0% reuse

(b) MAXIMUM FEASIBLE REUSE (%) AT 0.4 L/S PER FLOOR

Floors	100 mm	150 mm	200 mm
3	0	0	0
5	0	0	0
7	1	0	0
10	47	0	0
15	80	0	0
20	80	34	0

(c) MINIMUM BUILDING SIZE FOR VIABLE GREYWATER REUSE

Main Drain	Min Floors	Max Reuse	Notes
100 mm	7	1%	First viable level; meaningful reuse (47%) at 10+ floors
150 mm	20	34%	Not feasible below 20 floors
200 mm	Not viable	0%	Baseline velocity never reaches threshold

Notes: Values based on 0.4 L/s per floor, 2% slope, Manning's n = 0.013;

Challenge to conventional practice. These results fundamentally challenge current drainage design practice, which typically oversize pipes for safety margins. The finding that 200 mm drains preclude greywater reuse in buildings up to 20 floors reveals an unrecognized trade-off: conventional designs that "play it safe" with larger pipes inadvertently eliminate future greywater implementation by reducing baseline velocity below the self-cleansing threshold. This has significant implications for building codes, which often mandate minimum drain sizes based on peak flow capacity without considering the velocity impacts of water conservation measures.

Design guidelines. The parametric results yield practical guidelines for practitioners (Table 6). The critical first step is verifying that baseline drainage velocity exceeds 0.6 m/s. Without this step, greywater reuse is infeasible regardless of other design choices. Buildings with 3-5 floors cannot achieve feasible reuse with standard pipe sizing due to insufficient baseline velocity. Meaningful water savings (>30%) require 10+ floors with 100 mm drains or 20+ floors with 150 mm drains. Counter-intuitively, smaller drainage pipes enable greater reuse potential by maintaining velocity at reduced post-reuse flows; consequently, drain sizing should be based on anticipated post-reuse flows rather than pre-reuse peak demands.

For new construction targeting greywater reuse, the recommended design sequence is: (1) verify velocity feasibility, (2) define reuse targets, (3) size drains for post-reuse flows, then (4) design the potable supply system, which reverses the conventional approach. Retrofit projects with existing 150-200 mm drains are unlikely candidates unless the building exceeds 20 floors; building owners should begin feasibility assessments with drainage velocity analysis rather than water balance calculations, as a simple baseline velocity check can immediately indicate hydraulic viability.

Comparison to previous findings. These building-scale results align with Penn et al.'s (2013, 2014) municipal sewer studies showing that greywater reuse reduces downstream velocity and increases sedimentation risk. However, the present analysis reveals that velocity constraints are far more restrictive at the building scale, where total flows are lower and the margin above self-cleansing thresholds is minimal. While Penn et al. treated velocity reduction as a consequence to be managed through operational adjustments, this study reveals it as a binding constraint that determines maximum feasible reuse. This distinction fundamentally changes how practitioners should approach building-scale greywater system design.

Table 6. Design Guidelines for Practitioners

Category	Guideline
FEASIBILITY BY BUILDING CONFIGURATION	
3-5 floors, any drain	Not Viable: baseline velocity below threshold (0% savings)
7 floors, 100 mm	Marginally viable; verify baseline velocity (<1% savings)
10+ floors, 100 mm	Viable: meaningful reuse achievable (31-52% savings)
15-20 floors, 150 mm	Limited: only viable at 20 floors (0-22% savings)
Any height, 200 mm	Not Viable: consider smaller drain or higher demand (0% savings)
Retrofit, oversized drain	Unlikely feasible unless 20+ floors (likely 0% savings)
DESIGN RULES	
Critical first check	Verify baseline velocity > 0.6 m/s before planning greywater system
Minimum viable building	7+ floors with 100 mm drain; 20+ floors with 150 mm drain
Drain sizing principle	Size for post-reuse flow, not pre-reuse peak
Velocity safety margin	Target > 0.7 m/s baseline for design flexibility
Economic threshold	Generally viable for 10+ floor buildings with 100 mm drains
New construction sequence	(1) Check velocity; (2) Define reuse target; (3) Size drains; (4) Design potable system

Study Limitations and Future Work

The study scope includes important limitations. First, analysis focused on cold water systems, while hot water heating represents approximately 15-18% of total residential energy consumption and dominates water-related energy use because heating energy (~30-50 kWh/m³) exceeds pumping energy (0.2-0.5 kWh/m³) by an order of magnitude (EIA, 2018). Second, steady-state hydraulic analysis was employed, while hydraulic transients are common in premise plumbing (Lee et al., 2012). Third, single-building configurations with simplified geometry do not capture district-scale interactions or complex building layouts. Fourth, the 80% upper bound on greywater reuse may be conservative; higher rates may be feasible in taller buildings where the velocity constraint is not binding. Fifth, results depend on assumed values for Manning's roughness (0.013), pipe slope (2%), and the 0.6 m/s velocity threshold; sensitivity to these parameters warrants future investigation. Sixth, the analysis used minimum drainage velocity as the constraint criterion; in practice, self-cleansing may be achieved if peak velocity periodically exceeds 0.6 m/s during daily high-flow periods, which would expand the feasible design space. The self-cleansing velocity threshold (0.6 m/s) represents a commonly cited value, but actual thresholds may vary with wastewater characteristics and local code requirements; results should be interpreted with appropriate margins for site-specific conditions.

Despite these limitations, the work establishes the foundation for "One Water" concepts in building water systems. Future work should address: (1) hot water system integration with thermal-hydraulic coupling and *Legionella* risk assessment; (2) transient hydraulic analysis under time-varying demands; (3) district-scale optimization with multiple buildings; (4) sensitivity analysis across Manning's n (0.01-0.02), slope (1-3%), and demand variability; (5) alternative velocity criteria based on peak rather than conservative/ minimum flow conditions; (6) real building validation with monitored data; and (7) digital twin development with real-time control. These extensions will advance the vision of intelligent, autonomous building water systems.

Conclusion

This study addresses a critical gap in greywater reuse assessment: the impact of drainage self-cleansing velocity requirements on reuse feasibility. Through an integrated simulation framework coupling WNTR, PySWMM, and NSGA-II optimization across 72 building configurations, three key findings emerge. First, pump scheduling optimization alone achieves 83.7% energy reduction, indicating significant oversizing in baseline systems. Second, drainage velocity constraints impose the binding limit on greywater reuse, and this constraint is far more restrictive than previously recognized. For most low-rise buildings (3-5 floors), baseline velocity falls below the 0.6 m/s self-cleansing threshold, rendering greywater reuse infeasible with standard pipe sizing. Third, smaller drainage pipes enable greater reuse potential in taller buildings by maintaining adequate velocity at reduced post-reuse flows. This is a counter-intuitive finding that challenges conventional oversizing practices.

These findings yield two practical recommendations: (1) verify baseline drainage velocity exceeds 0.6 m/s before planning any greywater implementations, and (2) size drainage for post-reuse flows rather than pre-reuse peak demands. The parametric results provide practitioners with evidence-based guidelines to assess feasibility early in planning, preventing commitment to hydraulically infeasible reuse targets. By quantifying drainage-side constraints and demonstrating that they eliminate feasibility for most low-rise configurations, this work provides a more complete picture for integrated building water system design under "One Water" principles.

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Data Availability Statement

Data and analysis scripts are available from the author upon request.

References

Alfredo, K., Bedard, E., Buse, H. Y., Cazals, M., Francisco, P., Lee, J., Masters, S., Osann, E., Stillwell, A., Westerhoff, P., & Bartrand, T. A. (2025). Ten questions concerning water quality in building hot water systems. *Building and Environment*, *275*, 112803. https://doi.org/10.1016/j.buildenv.2025.112803

Bailey, O., Arnot, T. C., Blokker, E. J. M., Kapelan, Z., & Hofman, J. a. M. H. (2019). Predicting impacts of water conservation with a stochastic sewer model. *Water Science and Technology: A Journal of the International Association on Water Pollution Research*, *80*(11), 2148–2157. https://doi.org/10.2166/wst.2020.031

Bakheet, B., Prodanovic, V., Deletic, A., & McCarthy, D. (2020). Effective treatment of greywater via green wall biofiltration and electrochemical disinfection. *Water Research*, *185*, 116228. https://doi.org/10.1016/j.watres.2020.116228

Brock, C., Colsey, A., McGregor, E., Russo, S., Dandy, G., & Maier, H. (2012). *Multi-Objective Optimization of Integrated Water Reuse Systems at a Cluster Scale*. 909–920. https://doi.org/10.1061/41203(425)83

Chowdhury, R. K., & Rajput, M. A. (2016). Will greywater reuse really affect the sewer flow? Experience of a residential complex in Al Ain, UAE. *Water Supply*, *17*(1), 246–258. https://doi.org/10.2166/ws.2016.131

de Souza, D. F., da Guarda, E. L. A., Sauer, I. L., & Tatizawa, H. (2021). Energy Efficiency Indicators for Water Pumping Systems in Multifamily Buildings. *Energies*, *14*(21), 7152. https://doi.org/10.3390/en14217152

Deb, K., Pratap, A., Agarwal, S., & Meyarivan, T. (2002). A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation*, *6*(2), 182–197. https://doi.org/10.1109/4235.996017

Dev, A., Dilly, T. C., Bakhshipour, A. E., Dittmer, U., & Bhallamudi, S. M. (2021). Optimal Implementation of Wastewater Reuse in Existing Sewerage Systems to Improve Resilience and Sustainability in Water Supply Systems. *Water*, *13*(15), 2004. https://doi.org/10.3390/w13152004

EIA. (2018). *Space heating and water heating account for nearly two thirds of U.S. home energy use—U.S. Energy Information Administration (EIA)*. https://www.eia.gov/todayinenergy/detail.php?id=37433

Filho, F. J. C. M., Sobrinho, T. A., Steffen, J. L., Arias, C. A., & Paulo, P. L. (2018). Hydraulic and hydrological aspects of an evapotranspiration-constructed wetland combined system for household greywater treatment. *Journal of Environmental Science and Health, Part A*, *53*(6), 493–500. https://doi.org/10.1080/10934529.2017.1422954

Flörke, M., Kynast, E., Bärlund, I., Eisner, S., Wimmer, F., & Alcamo, J. (2013). Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. *Global Environmental Change*, *23*(1), 144–156. https://doi.org/10.1016/j.gloenvcha.2012.10.018

Friedler, E., & Hadari, M. (2006). Economic feasibility of on-site greywater reuse in multi-storey buildings. *Desalination*, *190*(1–3), 221–234. https://doi.org/10.1016/j.desal.2005.10.007

Ghisi, E., & Ferreira, D. F. (2007). Potential for potable water savings by using rainwater and greywater in a multi-storey residential building in southern Brazil. *Building and Environment*, *42*(7), 2512–2522. https://doi.org/10.1016/j.buildenv.2006.07.019

Gungor Demirci, G., Lee, J., & Keck, J. (2020). Optimizing pump operations in water distribution systems: Energy cost, greenhouse gas emissions, and water quality. *Water and Environment Journal*.

Gupta, R. (2017). *Hydrology and Hydraulic Systems, Fourth Edition, Waveland*. https://www.waveland.com/browse.php?t=384

Hadad, E., Fershtman, E., Gal, Z., Silberman, I., & Oron, G. (2022). Simulation of dual systems of greywater reuse in high-rise buildings for energy recovery and potential use in irrigation. *Resources, Conservation and Recycling*, *180*, 106134. https://doi.org/10.1016/j.resconrec.2021.106134

Khor, C. S., Akinbola, G., & Shah, N. (2020). A model-based optimization study on greywater reuse as an alternative urban water resource. *Sustainable Production and Consumption*, *22*, 186–194. https://doi.org/10.1016/j.spc.2020.03.008

Lee, J., Burkhardt, J., Buchberger, S., Grayman, W., Janke, R., Murray, R., & Platten, W. (2023). *Premise Plumbing Modeling*. ASCE.

Lee, J., Lohani, V. K., Dietrich, A. M., & Loganathan, G. (2012). Hydraulic transients in plumbing systems. *Water Science and Technology: Water Supply*, *12*(5), 619–629.

Leng, L., Jia, H., Chen, A. S., Zhu, D. Z., Xu, T., & Yu, S. (2021). Multi-objective optimization for green-grey infrastructures in response to external uncertainties. *Science of The Total Environment*, *775*, 145831. https://doi.org/10.1016/j.scitotenv.2021.145831

NAHB. (2019). *Multifamily Homes: Types and Trends*. https://www.nahb.org/other/consumer-resources/types-of-home-construction/multifamily

Oron, G., Or, Y., Shanni, J., Hadad, E., & Fershtman, E. (2024). Managing the kinetic energy of descending greywater in tall buildings and converting them into a valuable source. *Heliyon*, *10*(11), e31913. https://doi.org/10.1016/j.heliyon.2024.e31913

Parkinson, J., Schütze, M., & Butler, D. (2005). Modelling the Impacts of Domestic Water Conservation on the Sustain Ability of the Urban Sewerage System. *Water* *and Environment Journal*, *19*(1), 49–56. https://doi.org/10.1111/j.1747-6593.2005.tb00548.x

Penn, R., Friedler, E., & Ostfeld, A. (2013). Multi-objective evolutionary optimization for greywater reuse in municipal sewer systems. *Water Research*, *47*(15), 5911–5920. https://doi.org/10.1016/j.watres.2013.07.012

Penn, R., Hadari, M., & Friedler, E. (2012). Evaluation of the effects of greywater reuse on domestic wastewater quality and quantity. *Urban Water Journal*, *9*(3), 137–148. https://doi.org/10.1080/1573062X.2011.652132

Penn, R., Schütze, M., & Friedler, E. (2013). Modelling the effects of on-site greywater reuse and low flush toilets on municipal sewer systems. *Journal of Environmental Management*, *114*, 72–83. https://doi.org/10.1016/j.jenvman.2012.10.044

Penn, R., Schütze, M., & Friedler, E. (2014). Assessment of the effects of greywater reuse on gross solids movement in sewer systems. *Water Science and Technology: A Journal of the International Association on Water Pollution Research*, *69*(1), 99–105. https://doi.org/10.2166/wst.2013.555

Sabzkouhi, A. M., Lee, J., & Keck, J. (2022). Energy and Water Quality Management in Water Distribution Networks Considering Variable Speed Pump and Tank Flush Scheduling. *World Environmental and Water Resources Congress 2022*, 967–980.

UNESCO. (2024). *Statistics | UN World Water Development Report*. https://www.unesco.org/reports/wwdr/en/2024/s

United Nations. (2024). —*SDG Indicators*. https://unstats.un.org/sdgs/report/2025/Goal-06/

US Water Alliance. (2016). *One Water Roadmap: The Sustainable Management of Life’s Most Essential Resource*. https://uswateralliance.org/resources/one-water-roadmap-the-sustainable-management-of-lifes-most-essential-resource/

Zhang, D., Dong, X., Zeng, S., Wang, X., Gong, D., & Mo, L. (2023). Wastewater reuse and energy saving require a more decentralized urban wastewater system? Evidence from multi-objective optimal design at the city scale. *Water Research*, *235*, 119923. https://doi.org/10.1016/j.watres.2023.119923