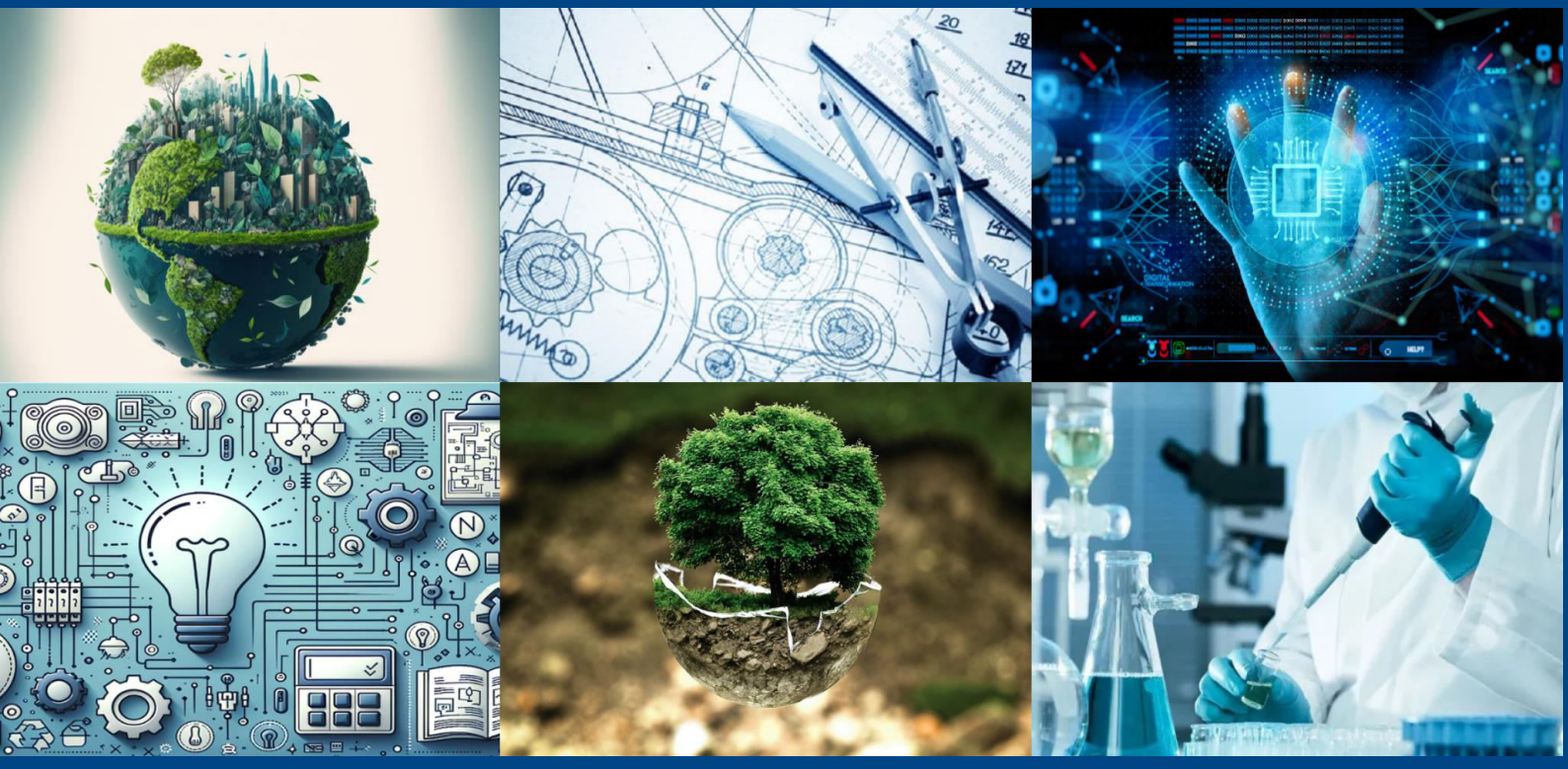
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Comprehensive Engineering Study for Sewerage Utility Modernization

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ABSTRACT: Pilgrimage hotspots face severe sewer overflows and river pollution caused by seasonal influxes of population. Municipal gravity sewers handling the flows from such load hubs are associated with excavation of large trenches and installation of heavy concrete pipes in order to carry off the heavy sediment cargo, constituting an unsustainable burden on the local municipality. The paper describes a small-bore sewerage scheme, which employs a passive surge-buffering interceptor tank with an appropriately sized orifice plate to the outlet. The tank is used to intercept solids and scum at the sewer inlet, while a throat tube at the tank outlet serves to choke peak flows and store temporal surpluses in the tank volume to equalize the discharge regime. The paper reports hydraulic performance studies demonstrating smooth flow characteristics and self-cleaning properties of smooth plastic pipes compared to concrete ones, as well as their advantage in terms of reduced hydraulic impact on downstream structures, including biotreatment systems.

I. INTRODUCTION

Municipal wastewater utilities in developing countries are confronted with the challenge of serving an exploding population with limited resources on hilly terrain. Conventional gravity sewerage (CGS) requires steep gradients to generate minimum self-cleansing velocities (0.60 to 0.75 m/s) needed to carry away raw solids. These constraints make CGS inappropriate for hilly areas as it involves deep trenches, large-diameter concrete pipes, and high-cost pumping stations, posing significant challenges to municipal authorities. Municipalities in developing countries face significant challenges upgrading or building new sewerage system infrastructure to meet the rising demand for sanitation services caused by urbanization and population explosions. This is especially true for the municipal wastewater utility in the holy city of Pandharpur, India, which experiences enormous fluctuations in populations due to the Wari Pilgrimage. The Wari festival, which takes place twice a year, attracts 500,000 to 1,000,000 temporary residents. The combined impact of these visitors and the permanent residents results in huge increases in wastewater flows (PF = 2.5) that overwhelm the city's sewerage system, resulting in frequent sanitary sewer overflows (SSOs) into the Chandrabhaga River. Small-bore sewerage (SBS) systems are a modular alternative to large-diameter CGS. SBS utilizes small-diameter plastic pipes (50 to 100 mm) to convey clarified effluent from primary septic tanks situated at relatively shallow depths (0.60 to 1.00 m) following the contour lines of the landscape. Small bore systems have been proven to be an affordable option for primary wastewater treatment. SBS systems are shallow and follow the contours of the landscape, necessitating the installation of manholes at strategic locations. The system is designed to handle intermittent flows from individual homes; hence it is typically not sized to accommodate simultaneous peak flows from all homes. Thus, when multiple upstream houses experience surpluses, the shallow pipe can overflow, causing downstream tanks to backflow. Though optimization studies have been made, the use of passive mechanical flow control devices at the outlets of septic tanks has not been explored.

II. LITERATURE REVIEW

2.1. Bouidi et al. (2026) applied a Lion Optimization Algorithm (LOA) to navigate discrete pipe sizes and slope limits in complex topographies. The study achieved cost reduction solely by altering excavation depths, overlooking the potential of source-level hydraulic dampening or settled sewerage.

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2.2. Karami et al. (2025) integrated smart, orifice-controlled micro-retention buffering tanks at major residential source connections using an Ant Colony Optimization (ACO) engine. The findings confirmed that source-level volumetric buffering dampens downstream peak surges, permitting a direct shift to smaller, shallow-buried pipelines.

2.3. Mohapatra et al. (2024) applied SewerGEMS dynamic modeling to forecast demographic loads and optimize pipe networks. The research emphasized that traditional high-diameter concrete piping imposes severe capital and excavation costs under elevated peak factors, supporting the rationale for smaller, alternative pipe materials like plastic conduits.

2.4. Mutikanga et al. (2023) investigated pilot SBS networks (75 mm to 100 mm PVC) across 120 serviced households in high-density informal settlements. The study demonstrated that removing settleable solids prevents deposition, validating that settled effluent remains self-cleansing at lower velocities (0.30 m/s) compared to conventional systems. Nevertheless, the system exhibited vulnerability to localized air-locking and vacuum issues during unmitigated morning discharge surges.

2.5. Sadeghi et al. (2022) utilized a modified multi-objective genetic algorithm (MOGA) paired with an EPA-SWMM routing engine to co-optimize network routing and pipe depth parameters, demonstrating a 12% to 15% reduction in trenching expenses. However, the framework demanded high computational run-times and remained confined to large-diameter, deep-trench systems.

2.6. Haghighi & Bakhshipour (2021) deployed a Grey Wolf Optimizer (GWO) linked with MATLAB hydraulic simulation matrices to minimize deep trenching in hilly topographies, achieving cost reduction solely by altering excavation depths without incorporating source-level hydrodynamic buffering.

Research Gap

Conventional municipal sewerage frameworks are completely reliant on capital-intensive downstream expansions (larger concrete trunk mains, deep excavation, and intermediate lift pumping stations) designed for a steady demographic growth, which proves inadequate against transient 5- to 10-fold festival population spikes. A critical research need was the development of an analytical and mathematically validated engineering framework which utilizes a passive, source-level choke mechanism (a calibrated sharp-edged orifice plate in combination with the available freeboard of primary interceptor tanks) to mechanically shave domestic surge hydrographs at the point of origin and thus avoid surcharging of subterranean networks as well as hydraulic washout of downstream biological treatment units by avoiding the use of energy-intensive electromechanical controls.

III. PROBLEM STATEMENT

Due to the large number of pilgrims in Pandharpur, the local sewer system experiences large-scale surges, which leads to overflow and consequent river pollution in the Chandrabhaga River, thereby not adhering to the environmental norms. Deep trench gravity sewers will be too expensive, and Small-Bore Sewerage does not provide localized control to mitigate the surges. Therefore, the main problem was the absence of an affordable, source-level surge attenuator that could passively manage the peak flows.

IV. OBJECTIVES

4.1.To design an orifice plate based on forecasted future wastewater loads.
4.2.To fabricate a prototype validating septic tank surge buffer performance.
4.3.To size SBS networks using Manning's equation and compare with concrete.
4.4.To evaluate the future scope and scalability of adopted techniques.

V. METHODOLOGY

The engineering process comprises of four stages which were determined by the research objectives of this study on sewerage utility modernization.

The first stage, leading to the achievement of objective one, involved carrying out a demographic survey, projecting geometric growth, and developing mathematical models of the orifice plate.

The second stage was aimed at fulfilling objective two and involved the development of mathematical models, non-stationary numerical approximation, and prototyping of the source surge buffer and orifice plate.

The third stage was meant to meet objective three and comprised of hydraulic sizing of small-bore sewage networks by applying Manning's equation to determine the size of smooth uPVC and concrete pipes.

The fourth stage was intended to achieve objective four and involved techno-economic evaluation, scalability analysis, and assessing the implementation boundaries for municipal sewerage utility modernization.

1.Demographic Forecasting & Orifice Parameter Calculation: To estimate future wastewater loads for the city of Pandharpur (Solapur district, Maharashtra) and define design conditions for the flow-restricting orifice, the population growth was projected using the official Census data and CPHEEO urban planning guidelines.

1.1 Demographic Growth Modeling: The municipal population growth was approximated using the geometric progression formula with the growth factor equal to the annual growth rate (r = 1.8% per annum or 0.018):

$$P_n = P_0(1 + r)^n$$

1.2.*Wastewater Load Forecasting:* The number of cubic meters of sewage was estimated using standard Class-I water allocation per capita and a municipal wastewater return fraction:

$$Q_{\text{future}} = P_n \times \text{LPCD} \times \eta$$

1.3.Orifice Design Boundary Parameters & Deficit Mapping: Accounting for extreme seasonal influxes (500,000 to 1,000,000 pilgrims) during the *Ashadhi* and *Kartiki Wari* festivals, a peak hydraulic factor ($PF = 2.5$) was applied to establish target restricted discharge rates. To verify subterranean hydraulic constraints, theoretical gravity capacities (Q_{existing}) of the existing aged concrete trunk network ($n_m = 0.015$) were calculated using Manning's equation:

$$\text{CSR} = \frac{Q_{\text{future_peak}}}{Q_{\text{existing}}} \quad \text{and}$$

$$\Delta Q = Q_{\text{future_peak}} - Q_{\text{existing}}$$

A condition of CSR > 1.00 or $\Delta Q > 0$ defines structural capacity failure, confirming that all evaluated existing concrete stretches fail capacity criteria under peak loads (CSR $= 1.34$ to 1.83).

2. Mathematical Modeling & Prototype Surge Buffer Mechanics:

To evaluate the prototype's ability to dampen peak flows before reaching dynamic software simulation tools, a first-order surge buffer model with an integrated calibrated orifice was developed.

2.1.Structural and Material Specifications: The conceptual interceptor prototype was designed with the following specifications:

2.1.1.Plan Dimensions & Surface Area (A_t): 3.0 m × 2.0 m plan geometry, yielding a surface footprint of $A_t = 6.0$ m^2.

2.1.2.Baffle & Solids Separation: An internal baffle plate separates settleable solids and floating scum, conveying clarified liquid to a submerged vertical T-pipe intake.

2.1.3.Calibrated Orifice Restrictor Plate: Machined from marine-grade Type 316 Stainless Steel (SS316, 4 mm thickness) with a concentric circular bore of $d_o = \emptyset 100$ mm ($A_o = 0.007854$ m^2).

2.1.4.Flange Coupling Assembly: Sandwiched between $\emptyset 100$ mm Schedule 80 uPVC threaded union flanges sealed with chemical-resistant EPDM rubber gaskets to prevent fluid bypass.

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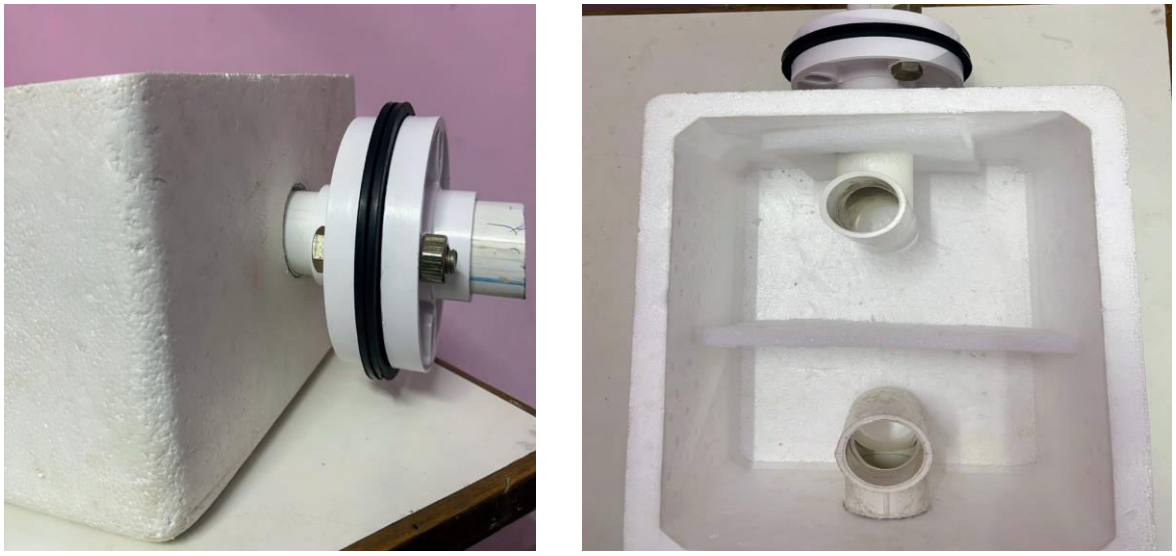


Figure 1: Modeling of Surge Buffer Mechanics

2.2 Non-Steady Discretized Continuity Formulation: The dynamic surge attenuation behavior was modeled using finite-difference approximations across discrete time steps ($\Delta t = 60$ s) under a simulated peak morning surge inflow $I_{\text{avg}} = 0.012$ m^3/s (12.00 L/s):

$$\Delta V = \left[I_{\text{avg}} - \left(C_d \cdot A_o \cdot \sqrt{2gh_{\text{avg}}}\right)\right]\Delta t$$

$$\Delta h = \frac{\Delta V}{A_t}$$

The maximum dynamic head rise ($h_{\text{max}} = 0.53$ m) was tracked against the provided design freeboard depth of 0.75 m (750 mm), ensuring that the dynamic surcharge remains safely below the invert level of domestic plumbing fixtures to eliminate back-siphonage.

3.Small-Bore Sewerage Hydraulic Sizing: uPVC vs. Concrete Comparison:

The carrying capacity and open-channel velocity profiles of the downstream Small-Bore Sewerage (SBS) collection network were evaluated using Manning's classical formula:

$$V = \frac{1}{n_m} \cdot R_h^{2/3} \cdot S^{1/2} \quad \text{and} \quad Q = A \cdot V$$

Comparative Material & Partial-Flow Evaluation: Hydraulic performance was comparatively assessed across pipeline materials:

Because solids are detained upstream, the network carries pre-settled effluent. Partial flow parameters were calculated at a design depth ratio of $d/D = 0.60$ (60% depth ratio per CPHEEO norms):

$$Q_{\text{design}} = 0.672 \times Q_{\text{full}} \quad \text{and} \quad V_{\text{design}} = 1.07 \times V_{\text{full}}$$

The resulting velocity (V_{design}) was benchmarked against the standard CPHEEO minimum self-cleansing velocity threshold ($V \geq 0.60$ m/s) to ensure stable, deposit-free gravity transport.

4.Future Scope, Scalability Assessment & Process Kinetics:

To evaluate the long-term expansion scope, techno-economic feasibility, and downstream process protection of the surge-buffering SBS methodology, three analytical assessments were executed:

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4.1.Downstream Biokinetic Modeling:

Using the stabilized inflow hydrograph provided by the orifice assembly, the required biological reactor volume (V_r) and Volumetric Organic Loading Rate (OLR) were determined using kinetic mass-balance equations for a Moving Bed Biofilm Reactor (MBBR):

$$V_r = \frac{Q_{\text{future}} \cdot (S_0 - S_e)}{X \cdot Y} \quad \text{and}$$

$$\text{OLR} = \frac{Q_{\text{future}} \cdot S_0}{V_r}$$

Hydraulic Retention Time (HRT) and BOD_5 removal efficiency were calculated to verify that upstream surge buffering prevents biokinetic washouts:

$$\text{HRT} = \left(\frac{V_r}{Q_{\text{future}}}\right) \times 24 \text{ hrs} \quad \text{and} \quad \text{Efficiency} = \left(\frac{S_0 - S_e}{S_0}\right) \times 100$$

4.2.Modular Scalability & Economic Viability Framework:

4.2.1.Decentralized Modular Rollout: Evaluating the technical feasibility of deploying localized, orifice-fitted interceptor tanks across individual household connections and high-density pilgrimage public toilet blocks.

4.2.2.Life-Cycle Cost Reduction: Contrasting the capital and operational expenditure profiles of shallow-buried uPVC Small-Bore Sewerage (0.60 to 1.00 m trench depths, no intermediate pumping) against conventional deep-trench concrete gravity sewers.

VI. RESULTS AND DISCUSSION

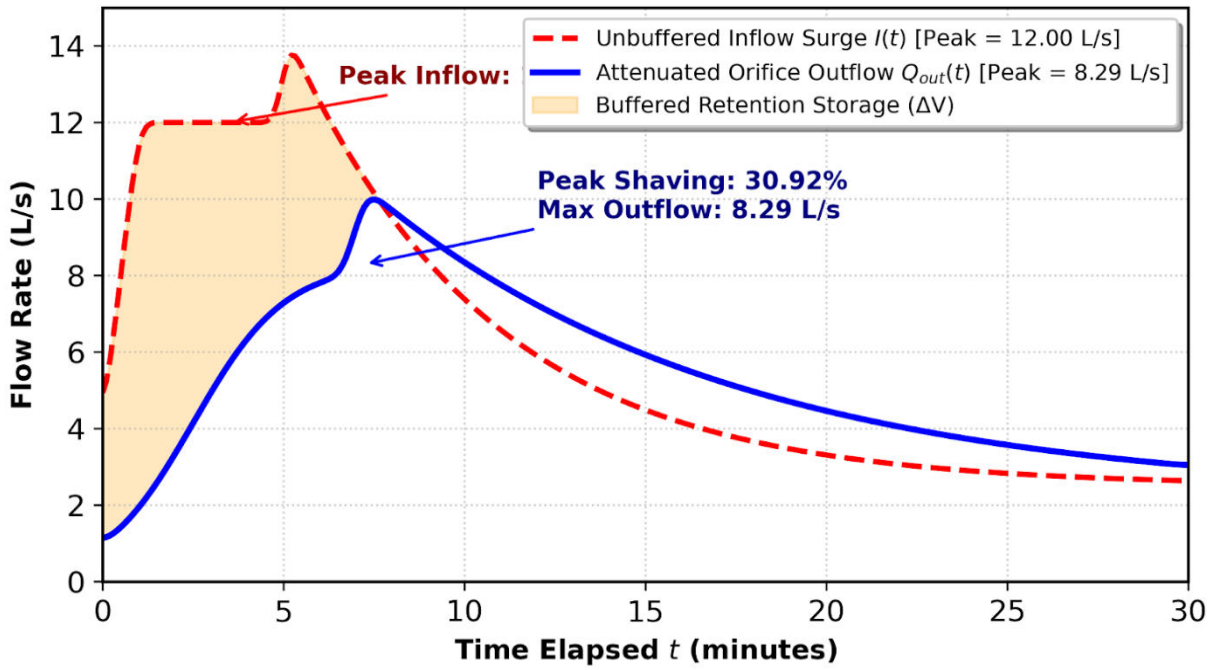


Figure 2: Dynamic Hydrograph Attenuation and Surge Shaving Curve

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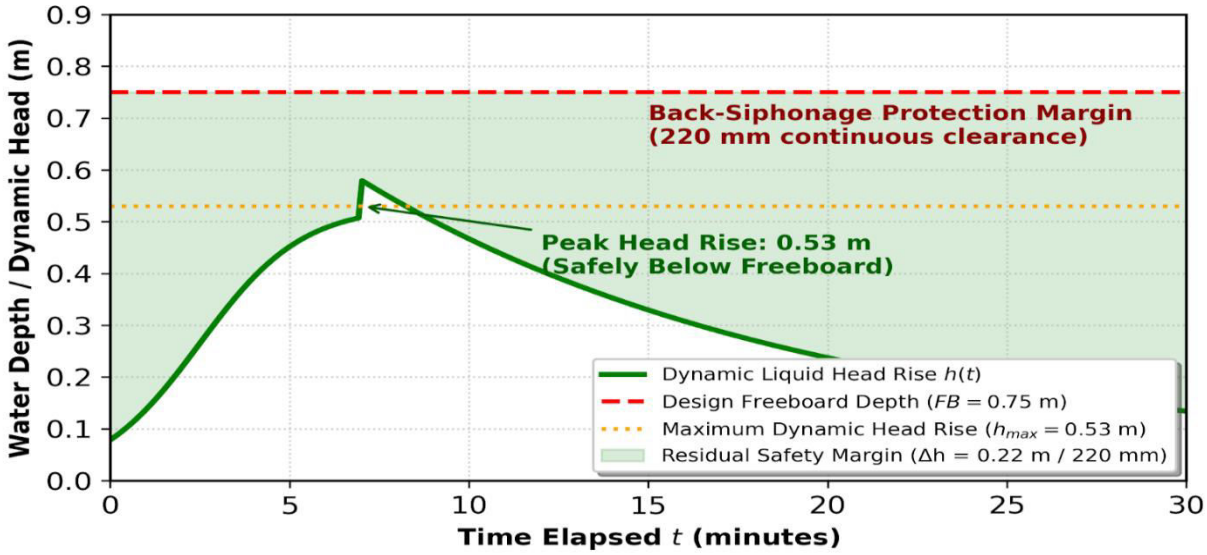


Figure 3: Comparative Open-Channel Flow Velocity Profiles Across Pipe Materials

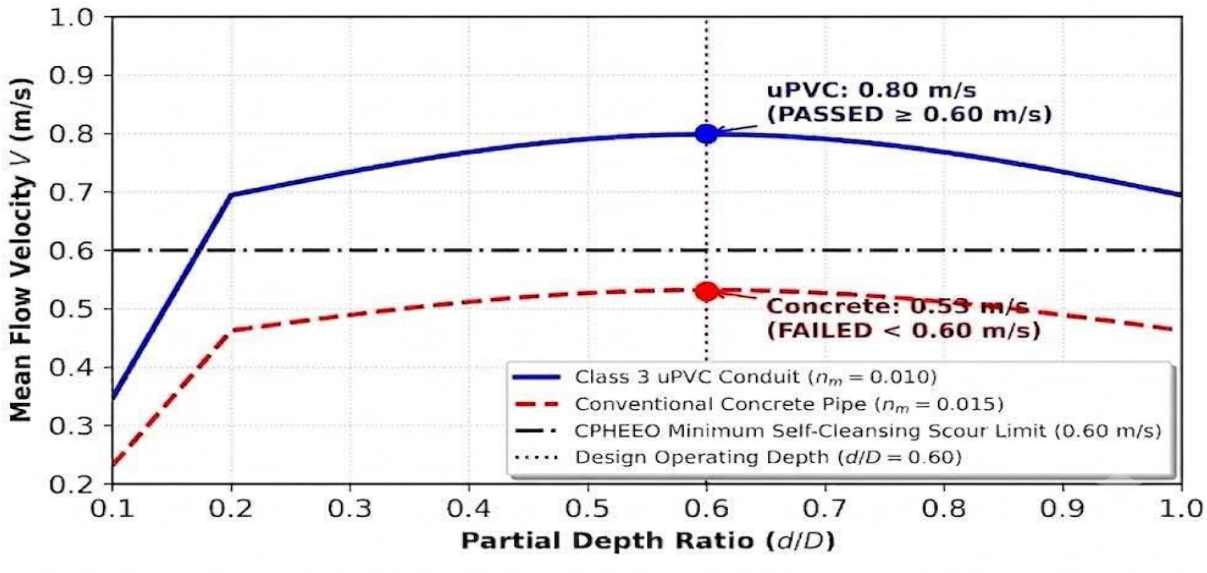


Figure 4: Interceptor Tank Dynamic Head Rise vs. Freeboard Safety Clearance

Phase / Objective	Core Parameter / Governing Equation	Calculated / Specified Boundary Value	Technical Standard / Justification
Phase I: Load Forecasting	Pn = P0(1 + r)^n | Qfuture = Pn · LPCD · η	P2056 = 220,713 persons | Q2056 = 23.84 MLD (23,837 m³/d)	Census 2011 (r = 1.8% per annum) | CPHEEO (135 LPCD, η = 0.80)
Phase II: Dynamic Orifice Buffer	ΔV = [Iavg - (Cd · Ao · √(2g · havg))] · Δt | Δh = ΔV / At	Ø100 mm SS316 Orifice Plate (Cd = 0.61) | hmax = 0.53 m; Freeboard = 0.75 m	30.92% peak flow reduction (12.00 → 8.29 L/s) | Prevents upstream back-siphonage

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Phase III: SBS Hydraulic Sizing	V = (1/nm) · Rh^(2/3) · S^(1/2) | Qdesign = 0.672 · Qfull (at d/D = 0.60)	Ø100 mm uPVC (nm = 0.010, S = 1:200) | Vdesign = 0.80 m/s; Qdesign = 3.94 L/s	Satisfies CPHEEO self-cleansing (≥ 0.60 m/s) | 40 mm crown headspace prevents surcharging
Phase IV: Process Kinetics	Vr = [Qfuture · (S0 - Se)] / (X · Y) | OLR = (Qfuture · S0) / Vr	Reactor Volume Vr = 1,900 m³ | OLR = 2.51 kg BOD5/m³·d; HRT = 1.91 h	95.0% BOD removal (Se ≤ 10 mg/L) | CPCB / MPCB surface water discharge norms

Table 1: Summary of Core Engineering Parameters, Governing Equations, and Design Benchmarks

Demographic Surcharging and Trunk Capacity Deficits: According to projections, the number of people is bound to increase, which will result in more wastewater produced in municipal networks. During peak times, due to the increased number of pilgrims, large volumes of water are added to the system, creating surges that are beyond normal rates. An analysis of the trunk's capacity shows that the old concrete pipes are completely unable to cope with the inflow of water under gravity. The imbalances are so significant that existing underground surcharges and deficits highlight that the basic gravity mains are unable to deliver the required performance.

Dynamic Orifice Attenuation and Hydraulic Safety: The finite difference method shows that installing an orifice attenuator on the outlet of the largest interceptor tank can regulate the inflow of wastewater. In the presence of large surges, the passive device reduces the outflow from the tank, thereby reducing the volume of water that needs to be pumped out. The dynamics of the water level in the tank ensure that the level does not rise above the design height, leaving a reserve to accommodate surges. At the same time, the height of the water column in the tank should not exceed the inlet level of the house connection. This ensures that the flow is not transferred back into the private or community network, eliminating the need for a vacuum pump and additional power.

SBS Conduit Hydraulics and Material Scour Considerations: As demonstrated by the analysis of open channel flows, the use of plastic conduits can ensure greater reliability and safety in the transportation of municipal wastewater. Compared to concrete, smoother plastic materials provide the required flow speed to ensure that deposits of impurities are not formed inside the pipe. At the same time, a comparative analysis of the allowable slope of concrete and plastic pipes shows that the flow velocity in concrete conduits is lower than in plastic ones. This means that concrete options cannot provide the required self-cleansing of the inner surface. In addition, the maintenance of freeboard made it possible to create a crown air gap, which allows the pipes to withstand pressure surges.

Biokinetic Reactor Stability Considerations: The presence of a throttling device upstream of the biological reactor ensures the stability of its work regime. Large surges of wastewater that come from the tank are attenuated, after which they flow evenly into the bioreactor. The hydraulic shock and associated variations in the volume of inflow have a lesser effect on the processes taking place inside the facility. Thus, the biological reactor is able to remove large amounts of organic wastewater components, ensuring high efficiency. At the same time, the loading of the volume of water flowing into the reactor is uniform, which is necessary for maintaining the processes inside it. This allows the bioreactor to maintain all characteristics of the effluent within the standard limits when discharged into natural waters.

VII. CONCLUSION

The present analysis proposes a sanitation upgrade framework for pilgrim-influenced municipalities based on the conversion from capital-intensive gravity sewers to a surge-absorbing small bore sewerage system. By applying the demographic projection, the model forecasts future generation requirements accurately capturing large-scale surcharging phenomena in the existing concrete pipelines. The calculated orifice plate area at the main septic tank outlets eliminates extreme domestic wastewater surges suppressing the temporal variability of the outflow hydrograph. A temporary storage of the episodic flow is accommodated safely in the freeboard of the septic tanks without reciprocating plumbing congestion. The open channel flow analysis confirms that small-diameter uPVC conduits can maintain self-cleansing velocities with sufficient interstitial space to absorb surcharging pressures at shallow burial depths compared to concrete pipes. Concurrently, the transformation of surges into steady flows prevents biological treatment systems from washouts

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while maintaining compliance with the receiving waters' discharge standards. Lastly, the source-level small bore sewerage scheme emerges as a technically viable and cost-effective solution for the municipal authorities by reducing excavation depths and eliminating pumping stations at intermediate lift points.

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