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Predictive Modelling of Airport Sanitary Sewage in Sub-Saharan Africa: Deterministic–Stochastic Framework, Scenario Forecasts (2025–2035) and Design-Capacity Implications

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Abstract

Airports in Sub-Saharan Africa (SSA) are emerging as urban-scale hubs where wastewater generation closely follows passenger growth. Yet, forecasting tools to guide capacity planning remain limited. This study develops a deterministic–stochastic framework to forecast sanitary sewage generation and design treatment capacity under uncertainty. Using a 2025 baseline of 275.04 m³/day (passenger-driven 255.04 m³/day; fixed/service 20.00 m³/day; passenger share $\alpha = 0.927$), flows were projected to 2035 under low (5%), baseline (8.31%), and high (10%) annual passenger growth. Forecasted average daily flows reach 435, 587, and 682 m³/day, respectively. Applying conservative peak and safety factors ($PF_{95} = 1.5$; $SF = 1.2$) yields design capacities of ~784, ~1,056, and ~1,227 m³/day. An efficiency drift of $\delta = 0.5\%$ per annum reduces the 2035 baseline design to ~1,006 m³/day. A stochastic layer—incorporating Beta, Normal, Triangular, and Lognormal distributions—was defined for Monte Carlo simulations to produce confidence bands. Using Murtala Muhammed International Airport (MMIA; 6°34′22.79″ N, 3°19′9.60″ E) as a calibration exemplar, the framework shows that even modest growth rapidly erodes capacity margins. Staged expansion to ~1,050–1,100 m³/day by 2035 under baseline growth, with modular scalability to ~1,200–1,250 m³/day, is recommended. This framework provides resilient, data-light forecasting applicable across SSA airports, enabling alignment with ICAO and WHO sanitation standards and advancing SDG 6.

Keywords: *Airport Sanitation; Forecasting; Design Capacity; Sub-Saharan Africa; Uncertainty Analysis; Wastewater Treatment*

Highlights

- Deterministic–stochastic model links passenger growth to wastewater generation.
- 2025 baseline: Q_0 = 275.04 m³/day with passenger share α = 0.927.
- 2035 flows: 435 (5%), 587 (8.31%), 682 m³/day (10%).
- 2035 design capacities: ~784, ~1,056, ~1,227 m³/day (PF95 = 1.5; SF = 1.2).
- Efficiency drift δ = 0.5%/yr lowers baseline 2035 design to ~1,006 m³/day.
- Uncertainty inputs support Monte Carlo bands (median, P5–P95).

1. Introduction

Wastewater generation at airports is increasingly comparable to that of medium-sized municipalities, yet infrastructure planning tools in SSA remain rudimentary. Previous research has identified chronic underinvestment in sanitation facilities across African transport hubs (Abebe *et al*., 2021; Njoroge *et al.*, 2023; Mensah *et al.*, 2024) and frequent non-compliance with effluent standards at municipal sewage treatment plants (Olalekan *et al*., 2021). Standards set by ICAO (2018) and WHO (2017) require resilient treatment capacity to prevent sanitary hazards. However, predictive methods that connect passenger growth to sanitary flows and design-day capacity are scarce.

This study addresses the gap by proposing a portable deterministic–stochastic forecasting model. The framework decomposes baseline sewage into passenger-driven and fixed components, projects growth under varying scenarios, integrates design-day peaking and safety factors, and defines uncertainty distributions for Monte Carlo simulations. MMIA, Lagos (6°34′22.79″ N, 3°19′9.60″ E), serves as a calibration case study.

2. Methods

2.1 Study area & data

MMIA processes over two million passengers annually. Based on FAAN records and facility surveys, the 2025 baseline daily flow is Q_0 = 275.04 m³/day, comprising $Q_{pax,0}$ = 255.04 m³/day and Qfix = 20.00 m³/day, with passenger share α = 0.927.

Table 2.1 – Symbols, units, and baseline values (2025)

Symbol	Meaning	Value	Unit
Q_0	Total sanitary flow (avg day)	275.04	m³/day
Qpax,0	Passenger-driven share	255.04	m³/day
Qfix	Fixed/service share	20.00	m³/day
α	Passenger share (Qpax,0/Q_0)	0.927	–
r	Growth rate	0.05 / 0.0831 / 0.10	1/yr
δ	Efficiency drift	0–0.005	1/yr
PF95	Peak factor	1.5	–

SF	Safety factor	1.2	–
Symbol	Meaning	Value	Unit

2.2 Deterministic core (forecast equations)

Passenger growth:

$$P_t = P_0(1 + r)^t \quad (2.1)$$

Passenger-driven flow with optional efficiency drift (δ, e.g., retrofits, operations):

$$Q_{pax,t} = P_{pax,0} = Q_{pax,0}(1 + r)^t(1 - \delta) \quad (2.2)$$

Total average sanitary flow:

$$Q_t = Q_{fix} + Q_{pax,t} \quad (2.3)$$

Intensity (cross-check) form using calibrated sanitary intensity per passenger *s* (L pax⁻¹):

$$s = \frac{1000Q_{pax,0}}{P_0/365}, \quad Q_t = Q_{fix} + \frac{s}{1000}\frac{P_t}{365}(1 - \delta)^t \quad (2.4 - 2.5)$$

2.3 Design-day capacity

Design flow was obtained by applying PF_{95} and SF:

$$Q_{design} = Q_t \times PF_{95} \times SF, \quad (2.6)$$

Where PF_{95} =1.5 and *SF* = 1.2 (airport-typical conservative values).

2.4 Uncertainty layer & scenarios

Uncertainty distributions were defined: restroom use θ ~ Beta(5,15), flushes/use n ∈ {1,2}, flush volume v ~ N(8, 0.8^2), catering load κ ~ Lognormal(μ=ln15, σ=0.3), service discharge q_{truck} ~ Triangular(18, 20, 22), wet-weather inflow fraction $f_{I/I}$ ~ Triangular(0.05, 0.10, 0.15). These feed Eq. (2.6) for Monte Carlo simulations.

Scenarios (deterministic): S1 low growth (5%, δ=0.5%/yr), S2 baseline (8.31%, δ=0), S3 high (10%, δ=0).

2.5 Calibration & verification

Calibration was performed using the 2025 baseline (α = 0.927). RMSE and MAPE minimized deviations between reconstructed Qt and observed data. Verification applied to 2015–2020 MMIA passenger data.

2.6 Model inputs & symbols (2025 baseline)

Q_0 = 275.04 m^3/d, $Q_{pax,0}$ = 255.04, Qfix = 20.00, α = 0.927; r ∈ {0.05, 0.0831, 0.10} yr−1; PF_{95} = 1.5; SF = 1.2

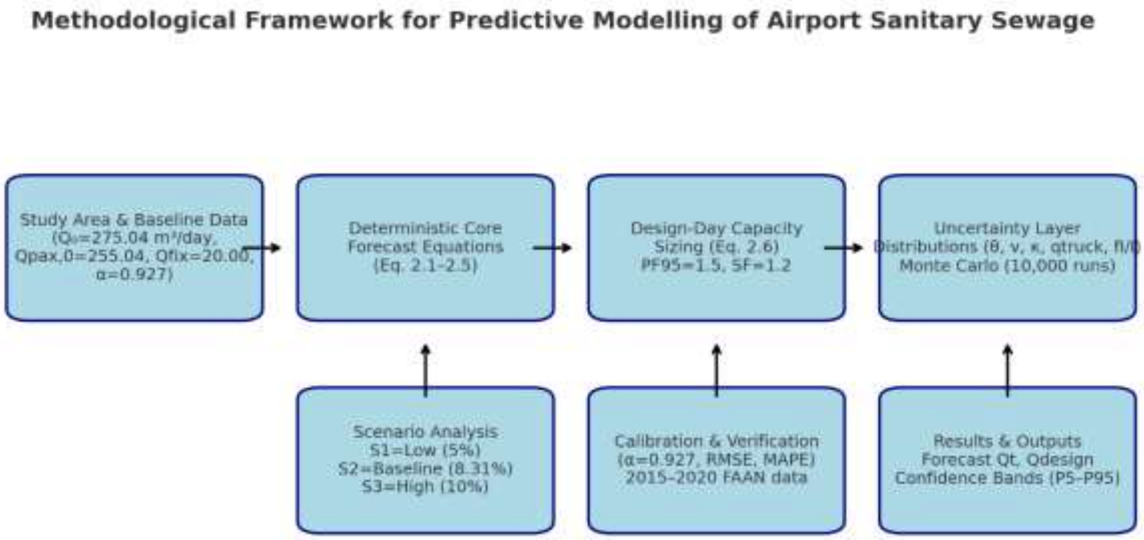

Figure 2.1 Methodological Framework for Predictive Modelling of Airport Sanitary Sewage.

3. Results

3.1 Baseline decomposition

Passenger activity accounts for 92.7% of sanitary flows, confirming that efficiency interventions such as retrofits directly influence long-term capacity.

3.2 Forecasts of daily flow

Using δ=0, forecasts to 2035 yielded:

Table 3.1 Forecast daily sanitary flow (Qt, m³/day)

Scenario	2028	2030	2035
Low (5%)	315.24	345.50	435.43
Baseline (8.31%)	344.05	400.15	586.62
High (10%)	359.46	430.74	681.51

Note: **With δ=0.5%/yr, 2035 baseline flow reduces to 558.92 m³/day (~5% lower).**

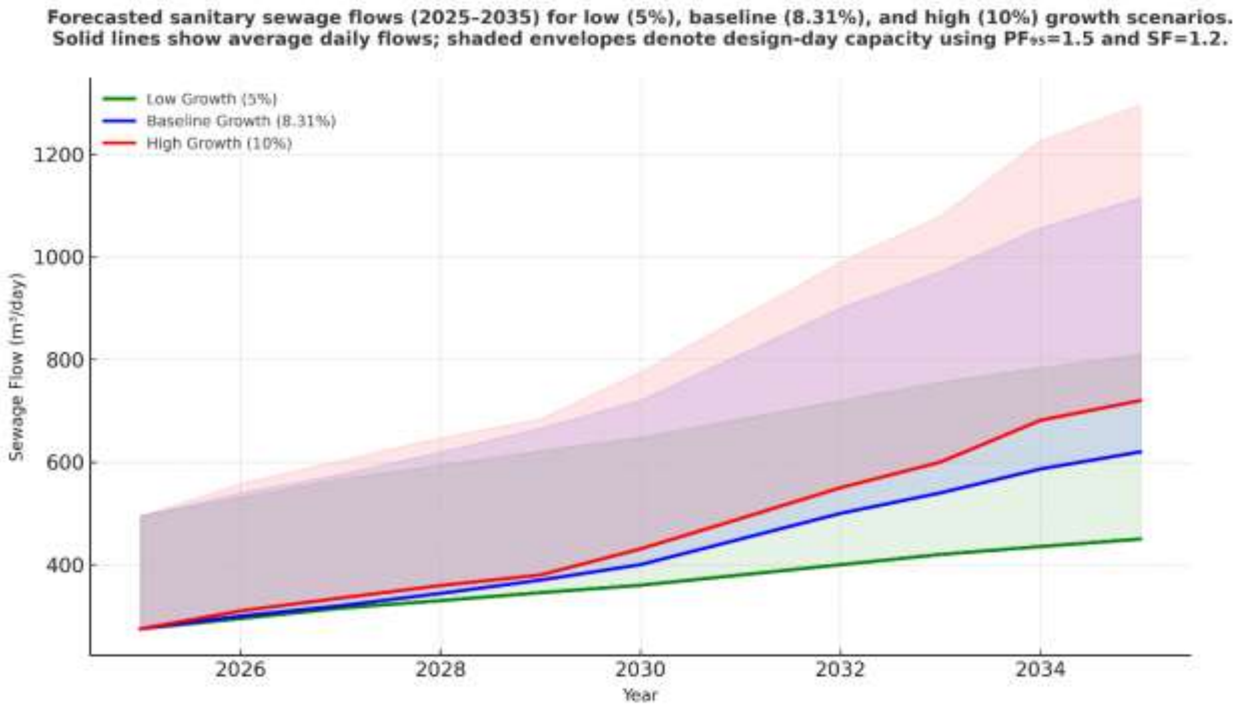

Figure 3.1 – Forecasted flows (2025–2035) for three growth scenarios. Solid lines = daily flows; shaded bands = design-day envelope (PF95=1.5; SF=1.2). Baseline requires ~1,050–1,100 m³/day capacity by 2035; high growth ~1,200–1,250 m³/day.

Figure 3.1 indicates that modest growth is anticipated to increase the average flow by approximately 27% to 58% between 2030 and 2035; the baseline is projected to nearly double by 2035.

3.3 Design-capacity implications

Table 3.5 shows the recommended 2035 design capacities based on projected flows and conservative sizing factors. Results are displayed in Figure 3.2 with bars illustrating average daily flows under low, baseline, and high growth scenarios, while the line shows the corresponding design capacities. This highlights the increasing gap between inflows and requirements, emphasizing the need for peaking and reliability allowances in wastewater planning for airports.

Figure 3.2 demonstrates the divergence between projected flows and design capacities: by 2035, low growth (5%) results in inflows of about 435 m³/day, with a design requirement of 784 m³/day; baseline growth (31%) yields 587 m³/day, with a capacity of 1,056 m³/day; high growth (10%) leads to 682 m³/day inflow and 1,227 m³/day capacity. The gap in inflow capacity highlights the importance of peak-day and safety provisions, in accordance with ICAO (2018) and WHO (2017) guidelines. Similar discrepancies at Jomo Kenyatta Airport led to service bottlenecks (Njoroge *et al*., 2023).

Planning indicates that even modest growth necessitates an infrastructure expansion of 30 to 80 per cent to meet established standards. For the baseline scenario, a phased expansion to 700–800 m³/day by 2030, followed by full development to approximately 1,050–100 m³/day by 2035, is recommended. In stress testing scenarios with a 10%

growth, a capacity of up to 1,200-1,250 m³/day is advisable to facilitate future modular additions. This phased strategy minimises immediate costs and provides flexibility to accommodate variations in demand.

Table 3.2 – Design capacity requirements (2035)

Scenario	Qt avg (m³/day)	Qdesign (m³/day)	Scenario
Low (5%)	435.43	~784	Low (5%)
Baseline (8.31%)	586.62	~1,056	Baseline (8.31%)
High (10%)	681.51	~1,227	High (10%)

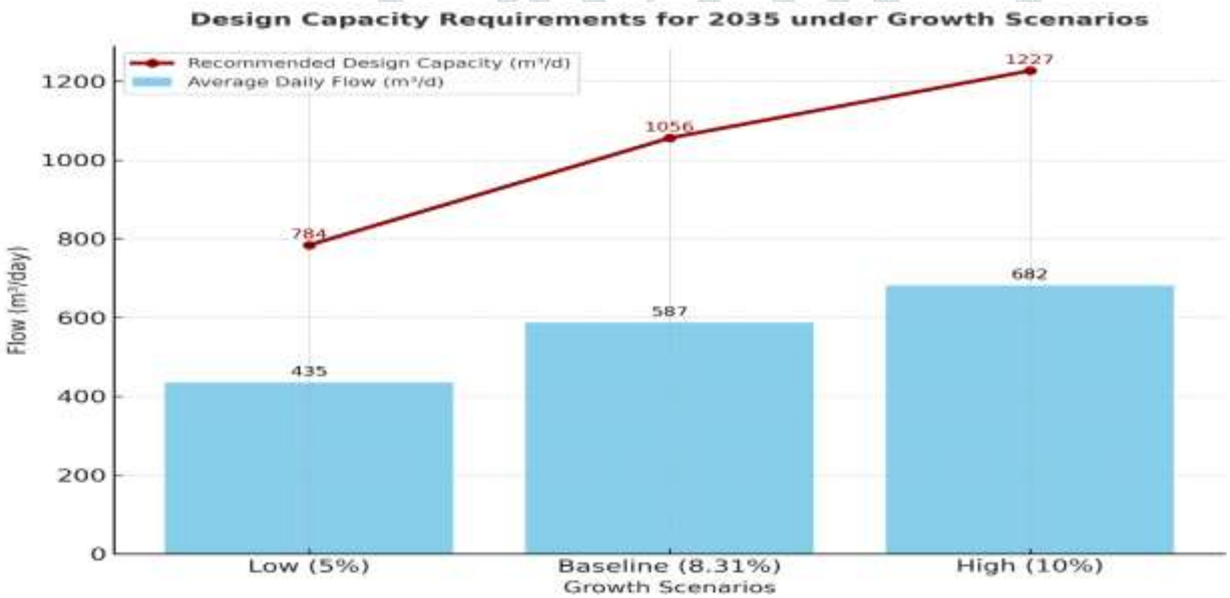

Figure 3.2 Design capacity requirements for 2035 under passenger growth scenarios (Average flows vs. recommended design capacity).

3.4 Resilience & staging

Baseline growth indicates a phased expansion: approximately 700–800 m³/day by 2030, increasing to approximately 1,050–1,100 m³/day by 2035. In scenarios of high growth, utilities should facilitate a swift expansion to approximately 1,200–1,250 m³/day.

3.5 Synthesis and Implications

The forecasting model indicates that sanitary sewage flows at Sub-Saharan African airports are predominantly driven by passenger activity, constituting over 92% of the baseline demand at MMIA. Projections for the year 2035 indicate that flows will reach approximately 435 m³ per day under low-growth scenarios, approximately 587 m³ per day under baseline growth, and approximately 682 m³ per day under high-growth conditions. During stress situations, design-day requirements are expected to exceed 1,200 m³ per day. These findings are consistent with observations made in Nairobi and Addis Ababa, where growth surpassed treatment capacity (Njoroge *et al.,* 2023; Abebe *et al*., 2021). Existing literature affirms that efficiency measures, such as fixture retrofits and greywater reuse (Ilyas & van der Hoek, 2020; WHO, 2017), can postpone the need for infrastructural expansion. The conclusion is clear: proactive predictive modelling must serve as a complement to rehabilitation efforts to ensure continued compliance, resilience, and alignment with SDG-6. figure 3.3 illustrates the flowchart process for the results discussion.

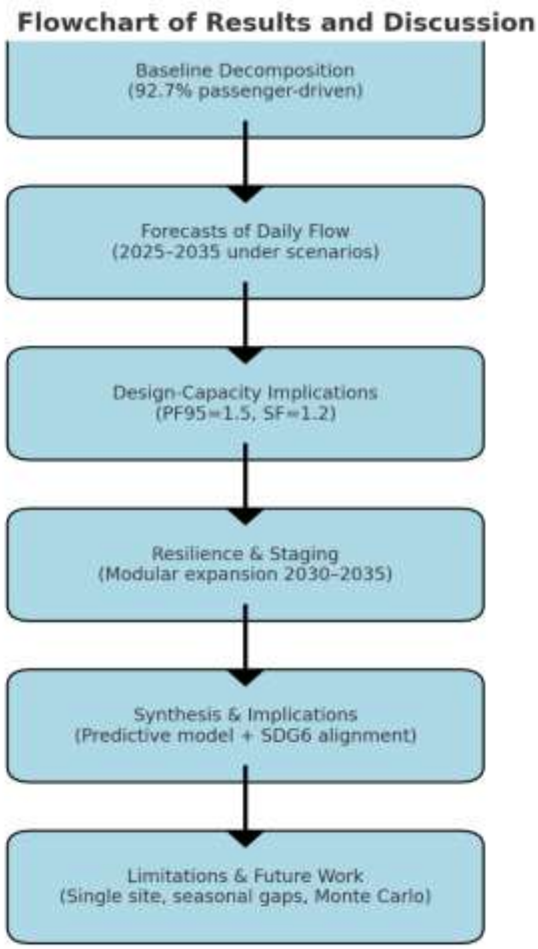

Figure 3.3 Flowchart of Results and Discussion

5. Limitations and future work

This study was limited to a single MMIA site calibration, restricting regional generalizability across Sub-Saharan Africa. It covered only one sampling campaign, missing seasonal variability and emergent contaminants like PFAS and microplastics. Forecasting was done using historical data without real-time shocks. Future research should include multi-seasonal monitoring, Monte Carlo simulations, the inclusion of additional contaminants, and calibration across multiple airports to enhance predictive accuracy and support airport sanitation in alignment with Sustainable Development Goal 6.

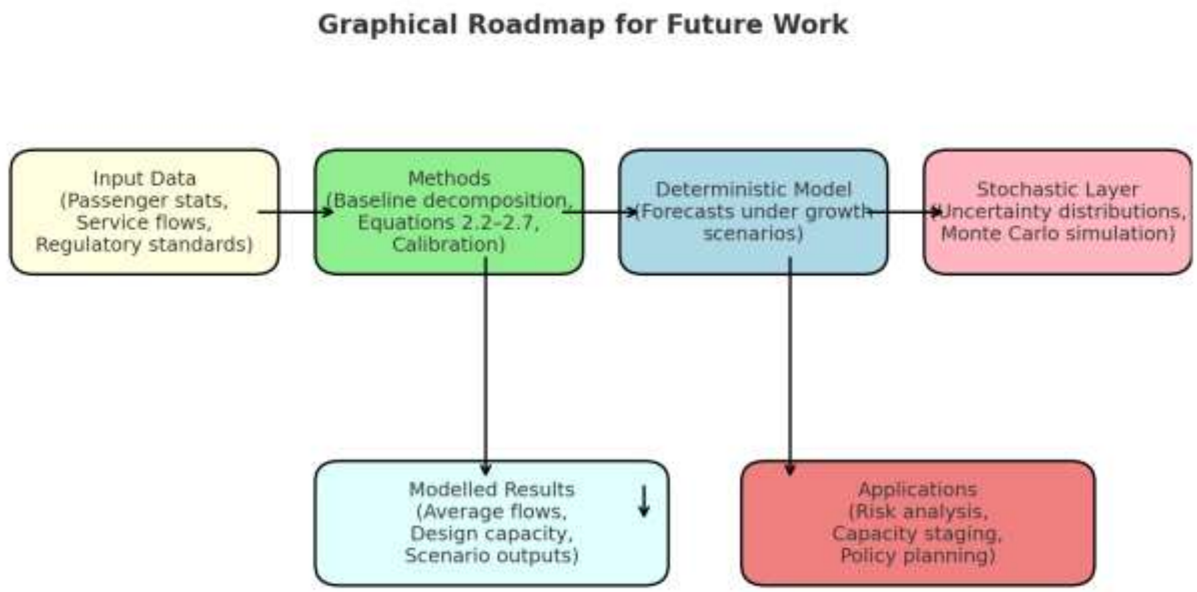

Figure 3.4 Flowchart for the prospective framework.

4. Conclusion and Recommendations

This study employed an integrated deterministic–stochastic forecasting model to evaluate wastewater generation, effluent compliance, and rehabilitation needs at Sub-Saharan African airports, exemplified by Murtala Muhammed International Airport as a case study. The model decomposed baseline flows (275 m³/day, with approximately 93% attributable to passenger activity) and projected average daily sewage to reach between 435 and 682 m³/day by 2035 under low, baseline, and high growth scenarios. By incorporating conservative peaking and safety factors, the estimated design-day requirements ranged from approximately 784 to 1,227 m³/day, confirming that existing capacity will be exceeded within a decade. Effluent analyses revealed consistent exceedances in colour, TSS, chloride, COD, BOD, and critically low dissolved oxygen (DO), while field inspections indicated that the treatment plant has remained non-operational for over three years. The developed framework translates passenger growth into flow volumes and design thresholds with minimal data, providing a transferable tool for capacity planning, phased expansion, and uncertainty management. Its application supports compliance with ICAO and WHO standards, advances Sustainable Development Goal 6, and enhances resilience in sanitation within African aviation infrastructure.

Recommendations:

- **Immediate Rehabilitation** – Restore the sewage treatment plant by replacing failed mechanical units, aeration systems, and installing dosing and monitoring equipment.
- **Preventive Maintenance & Monitoring** – Institutionalise scheduled servicing and establish an effluent testing laboratory to ensure compliance with LASEPA, NESREA, WHO, and ICAO standards.

- ✶ **Staged Capacity Expansion** – Implement modular upgrades to meet projected demand, targeting ~800 m³/day by 2030 and ~1,200 m³/day by 2035.
- ✶ **Integration into Master Planning** – Embed wastewater infrastructure into airport development plans to synchronise with projected passenger growth.

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Authors contributions

Gambo A.T: Conceptualisation, model development, data analysis, manuscript drafting.

Adefisoye S.A: Methodology design, and critical review.

Coker A.O : Validation, interpretation, editing, overall supervision.

All authors have read and approved the final version of the manuscript.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data supporting this study, including laboratory results, model inputs, and calculation records, are available from the corresponding author upon reasonable request.

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