

Assessment of Hybrid Wastewater Treatment Systems: Integrating Constructed Wetlands for Improved Effluent Quality in Lusaka, Zambia

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ABSTRACT

Urban wastewater treatment systems in rapidly growing African cities often face operational and capacity constraints, resulting in the discharge of inadequately treated effluent into receiving watercourses. This study assessed the operational performance of the Manchinchi Wastewater Treatment Plant (WWTP) in Lusaka, Zambia, characterised its impact on the Ngwerere Stream, and designed a horizontal subsurface-flow constructed wetland (HSSF-CW) as a downstream polishing stage. Effluent and stream water quality were sampled during the 2024/2025 dry season at three WWTP stations and ten stream stations, and analysed for BOD₅, TSS, dissolved oxygen and nutrients against Zambia Environmental Management Agency (ZEMA) discharge standards. Results showed severe organic pollution, with WWTP effluent BOD₅ of 600-629 mg/L against a ZEMA limit of 50 mg/L, near-zero dissolved oxygen at the discharge points, and BOD₅ concentrations of 240-290 mg/L immediately downstream in the Ngwerere Stream. Using a temperature-corrected first-order areal kinetic model, a 24.7-ha HSSF-CW was designed, with a predicted BOD₅ removal efficiency exceeding 91%, reducing effluent BOD₅ from 600 mg/L to below 54 mg/L within a hydraulic retention time of approximately 2.0 days. The 24.7-ha land requirement is identified as the principal feasibility constraint for application in peri-urban Lusaka. Modular cell construction intensified (vertical-flow or aerated) wetland configurations, and restoration of the WWTP's existing secondary treatment units are recommended to reduce the land footprint. The findings support the integration of nature-based polishing systems with conventional infrastructure as a practical pathway toward ZEMA compliance and Zambia's Vision 2030 sanitation targets.

Keywords: Hybrid wastewater treatment; Constructed wetlands; Nature-based solutions; Effluent quality; Sanitation

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1. INTRODUCTION

Rapid urbanisation across sub-Saharan Africa has placed severe and growing pressure on wastewater treatment infrastructure. Cities are expanding far faster than supporting sanitation systems, leaving wastewater treatment plants (WWTPs) chronically overloaded, under-resourced, and unable to meet discharge standards. The result is the routine release of poorly treated effluent into rivers, streams, and peri-urban environments, degrading aquatic ecosystems, threatening public health, and undermining progress toward the Sustainable Development Goals (UN-Habitat, 2023). In Zambia, a national sanitation audit found that approximately 75% of districts lack dedicated sanitation systems, and 24% possess only partially functioning infrastructure due to age-related deterioration and funding constraints (Republic of Zambia, 2022).

In Lusaka, the Manchinchi Wastewater Treatment Plant (WWTP) serves a significant portion of the city's sewered population and discharges treated effluent into the Ngwerere Stream, a tributary of the Chongwe River used by downstream communities for agriculture, livestock watering, and domestic activities. Despite its importance, the plant has operated under sustained hydraulic overload, with ageing infrastructure and limited maintenance collectively reducing treatment efficiency. Effluent quality frequently exceeds regulatory discharge limits set by the Zambia Environmental Management Agency (ZEMA), with BOD₅ and suspended solids concentrations orders of magnitude above permissible thresholds.

Nature-based solutions (NbS), and constructed wetlands (CWs) in particular, have emerged as effective, low-cost, and sustainable complements to conventional wastewater treatment (Boano et al., 2020). Constructed wetlands are engineered systems that replicate the biogeochemical processes of natural wetlands, using macrophytes, substrate media, and microbial communities to remove pollutants from wastewater (Vymazal et al., 2021). They offer significant advantages in low- and middle-income country contexts: low energy consumption, minimal mechanical complexity, tolerance of variable influent loads, and the capacity to provide co-benefits, including habitat creation and landscape enhancement (Biswal & Balasubramanian, 2022; Kabisch et al., 2022). When integrated downstream of conventional WWTPs as a polishing stage, a configuration termed a hybrid wastewater treatment system, constructed wetlands can achieve BOD reductions exceeding 80% and deliver effluent quality approaching or meeting discharge standards (Fernandez-Fernandez et al., 2020).

Despite these demonstrated benefits, published evidence on hybrid WWTP-CW systems in urban African contexts remains limited, and most design parameters in use have been derived from temperate or European studies (Lema, 2025; Muwanga Tebitendwa & Cowan, 2021). This gap is directly relevant to the ZAWAFE 2026 theme, “From Commitment to Action: Accelerating Integrated Resilience Solutions for Vision 2030 and the SDGs, as well as Inclusive and Sustainable Sanitation Solutions,” as it demonstrates a low-cost, locally adaptable engineering intervention that converts diagnostic evidence of sanitation failure into an actionable, nature-based resilience solution for urban sanitation and water resource management.

This study aimed to: (i) assess the operational performance and effluent quality of the Manchinchí WWTP against ZEMA discharge standards; (ii) characterise the resulting water quality impacts on the Ngwerere Stream; and (iii) design and predict the performance of a horizontal subsurface-flow constructed wetland (HSSF-CW) as a polishing unit to bring effluent quality into regulatory compliance. Together, these components constitute an integrated hybrid treatment assessment directly relevant to wastewater management challenges in Lusaka and comparable rapidly urbanising African cities.

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted at the Manchinchí Wastewater Treatment Plant and along the Ngwerere Stream between September and October, in Lusaka District, Zambia. The Ngwerere Stream is a major tributary of the Chongwe River, flowing approximately 41 km through urban and peri-urban Lusaka before draining into the Chongwe River, itself a tributary of the Zambezi River (Tena et al., 2021). Part of Lusaka city sits on the headwaters of the Ngwerere Stream, located between latitudes 15.16°S and 15.5°S and longitudes 28.17°E and 28.5°E at an elevation of approximately 1,280 m. The city experiences a distinct dry season from May to October, during which streamflows are at their lowest and pollutant concentrations in receiving waters are highest due to reduced dilution. Annual average rainfall is approximately 882 mm, concentrated in the wet season (November–April).

The Manchinchí WWTP is operated by the Lusaka Water Supply and Sanitation Company (LWSC) and represents the primary point-source discharge impacting the Ngwerere Stream within the study reach. The treatment train comprises coarse screening, grit chambers, primary sedimentation, trickling filters, anaerobic digesters, wastewater stabilisation ponds, and sludge drying beds. Average influent flow is approximately 0.385 m³/s (33,300 m³/day).

2.2 Field Sampling and Laboratory Analysis

Water quality samples were collected during the dry season of the 2024/2025 water year, between May and October, the critical period of maximum pollutant concentration and minimum stream dilution, from three locations at the WWTP (influent and two effluent discharge points) and from ten stations along the Ngwerere Stream spanning upstream and downstream of the discharge point (P1–P10). Sampling followed a purposive strategy based on hydrological significance and site accessibility. Grab samples were collected at mid-depth and mid-channel locations, with an average channel width of 7 m and depth of 0.2 m and preserved at 4°C for transport to the University of Zambia (UNZA) Environmental Engineering Laboratory. All samples were analysed within six hours of collection.

Parameters analysed included biochemical oxygen demand (BOD₅) using the five-day incubation method, dissolved oxygen (DO) by Winkler titration, total suspended solids (TSS) by gravimetric

analysis, ammonium nitrogen (NH₄-N), nitrate nitrogen (NO₃-N), total phosphorus (TP), pH, and temperature. All analyses followed Standard Methods for the Examination of Water and Wastewater (APHA, 2017). Results were compared against ZEMA regulatory discharge standards (Government of Zambia, 2011; ZEMA, 2013). A site visit and operational inspection of the WWTP were conducted alongside sampling to document the functional status of each treatment unit.

2.3 Hybrid System Design: Constructed Wetland

A horizontal subsurface flow constructed wetland (HSSF-CW) was designed as a polishing unit to be positioned downstream of the Manchinci WWTP before discharge into the Ngwerere Stream. The HSSF configuration was selected based on its established performance for BOD and suspended solids removal, its compatibility with gravity-driven flow (eliminating energy requirements), reduced surface exposure (minimising odour and mosquito breeding risk), and its suitability for warm tropical climates.

Wetland sizing was performed using the first-order areal kinetic model, which describes the exponential decay of pollutant concentration as wastewater travels through the subsurface media (Equation 1). This model is the most widely validated and applied approach for HSSF-CW design and has been confirmed as reliable for BOD removal prediction across a broad range of tropical and subtropical wetland systems (Abdul Aziz et al., 2022; Soares et al., 2022).

$$A = (Q / k) \times \ln(C_0 / C) \quad (1)$$

Where A = required wetland surface area (m²); Q = effluent flow rate (m³/day); k = temperature-corrected first-order areal rate constant (m/day); C_0 = influent BOD₅ concentration (mg/L); C = target effluent BOD₅ concentration (mg/L).

First-order rate constants were sourced from peer-reviewed analyses of HSSF-CW systems treating municipal wastewater in tropical and subtropical climates (Ventura et al., 2022; Singh et al., 2022). A conservative mid-range design value of $k_{20} = 0.25$ m/day was adopted. Temperature correction was applied using the Arrhenius relationship, $k_t = k_{20} \times \theta^{(T-20)}$, where $\theta = 1.06$ and $T = 25^\circ\text{C}$ (representative of Lusaka's dry-season conditions), yielding $k_t = 0.335$ m/day. Influent concentration ($C_0 = 600$ mg/L) was taken from measured WWTP effluent data. The target effluent concentration ($C = 50$ mg/L) was set in line with the ZEMA discharge standard for BOD₅. Wetland media were specified as gravelly sand with a porosity of 0.38 and a water depth of 0.7 m, consistent with standard HSSF design guidelines (El-Khateeb, 2024; USA EPA Office of R&D, 1998). A length-to-width ratio of 3:1 was adopted to minimise hydraulic short-circuiting. Hydraulic retention time (HRT) was calculated using Equation 2.

$$\text{HRT} = (n \times A \times d) / Q \quad (2)$$

Where n = porosity of the media; A = surface area of the media (m²); d = depth of the media (m); Q = design flow rate (m³/day).

3. RESULTS AND DISCUSSION

3.1 WWTP Operational Assessment

Field inspection of the Manchinchí WWTP revealed systemic operational failures across the entire treatment train. Table 1 summarises the observed failures by treatment unit.

Table 1: Operational failures observed at the Manchinchí WWTP during field assessment

Treatment Unit	Expected Function	Observed Failure
Inlet Screening	Removal of solids and debris	Only one of two channels operational; hydraulic overloading; frequent screen blinding
Grit Chambers	Removal of heavy particles (sand, grit)	Mechanical scrapers non-functional; manual removal required; sediment accumulation
Primary Sedimentation	Gravity settling of suspended solids	Sludge accumulation: TSS removal below expected 50-60%; uneven flow distribution
Sludge Pumping	Regular sludge withdrawal	Irregular desludging; intermittent pump operation; solids carry-over to effluent
Secondary Treatment (Trickling Filters)	Aerobic biodegradation of organic matter	Completely non-functional during assessment; negligible BOD reduction achieved
Stabilisation Ponds	Final aerobic stabilisation	Hydraulic overloading, poor maintenance, odour generation, incomplete oxidation
Drying Beds	Sludge dewatering	Insufficient capacity; extended drying times; sludge backup into treatment train

The most critical failure was the complete non-functionality of the secondary treatment trickling filters, the primary unit process responsible for biological BOD removal. Without effective secondary treatment, the plant was essentially operating as a primary-only system, achieving only partial removal of suspended solids through sedimentation while discharging the bulk of the organic load to the receiving stream. Field observations, including worn mechanical distributor components, deferred maintenance, and irregular sludge handling across the train, point to a combination of ageing infrastructure, constrained maintenance budgets, and possible power supply interruptions as the likely drivers of trickling-filter failure. This is consistent with documented patterns across WWTPs in sub-Saharan Africa, where these same factors routinely reduce treatment effectiveness to below design standards (Haileselassie et al., 2025; Cavil Sue et al., 2019; Jaskulak et al., 2022). Hydraulic overloading, evidenced by the non-functional inlet channel and overloaded stabilisation ponds, further compounds treatment failure by reducing contact time in each unit process, a known driver of effluent non-compliance in municipal WWTPs operating beyond design capacity (Collivignarelli et al., 2023).

3.2 Effluent Quality and Stream Impacts

The measured water quality parameters at the WWTP and upstream Ngwerere Stream, relative to ZEMA discharge standards, are presented in Table 2.

Table 2. Measured water quality parameters against ZEMA discharge standards

Parameter	WWTP Influent	WWTP Effluent (avg.)	Ngwerere Upstream	ZEMA Limit
BOD ₅ (mg/L)	860	600	30	50
TSS (mg/L)	1,054	769	104	100
DO (mg/L)	0	0	0.3	≥ 5
NH ₄ -N (mg/L)	8.97	8.60	8.59	10
NO ₃ -N (mg/L)	11.55	10.0	2.66	10
TP (mg/L)	4.31	2.55-2.62	0.27	5
pH	8.03	8.0	7.56	6-9
Temperature (°C)	17.4	18.0-18.5	16.8	≤ 35

ZEMA: Zambia Environmental Management Agency; DO: dissolved oxygen; BOD₅: five-day biochemical oxygen demand; TSS: total suspended solids; NH₄-N: ammonium nitrogen; NO₃-N: nitrate nitrogen; TP: total phosphorus. Values are dry-season averages from field sampling.

Effluent BOD₅ concentrations of 600 mg/L exceeded the ZEMA limit of 50 mg/L by a factor of twelve, confirming critically poor organic matter removal. TSS concentrations of 769 mg/L were nearly eight times the permissible 100 mg/L. Dissolved oxygen was at or near zero at all effluent sampling points, reflecting the severe oxygen demand of the discharged organic load and the absence of any post-treatment aeration. These conditions are directly attributable to the secondary treatment failures described in Section 3.1. Notably, nutrients (NH₄-N, NO₃-N, TP) remained within ZEMA limits at the effluent discharge points, indicating that nutrient removal is not the primary compliance challenge; organic matter and suspended solids are the critical parameters requiring intervention.

The impact on the Ngwerere Stream was pronounced. Even upstream of the discharge point, DO levels were low (0.3 mg/L), reflecting cumulative inputs from multiple urban discharge sources within the catchment. Immediately downstream of the Manchinci WWTP discharge, BOD₅ concentrations in the stream reached 240-290 mg/L, far exceeding background conditions. These elevated organic concentrations rapidly depleted dissolved oxygen in the downstream reach, confirming that the

Ngwerere Stream has severely limited assimilative capacity during dry-season low-flow conditions (mean dry-season flow: 0.304 m³/s). Partial DO recovery was observed further downstream (6.0–6.6 mg/L at the outlet, approximately 39 km downstream), attributable to natural re-aeration, reduction in organic loading with distance, and photosynthetic oxygenation, consistent with the classical Streeter–Phelps oxygen sag model (Streeter & Phelps, 1925; Streeter-Phelps equation, n.d.) and with findings from comparable African urban streams (Angello et al., 2021; Waturu et al., 2022).

3.3 Constructed Wetland Design and Performance Prediction

The full set of design parameters and outputs for the HSSF-CW is shown in Table 3.

Table 3. HSSF-CW design parameters and predicted performance

Design Parameter	Value / Unit
CW Configuration	Horizontal Subsurface Flow (HSSF)
Vegetation Species	Phragmites australis
Substrate / Media	Gravelly sand; porosity (n) = 0.38
Influent BOD ₅ (C ₀)	600 mg/L (measured WWTP effluent)
Target Effluent BOD ₅ (C _e)	50 mg/L (ZEMA discharge standard)
Design Flow Rate (Q)	33,300 m ³ /day
Design Rate Constant at 20°C (k ₂₀)	0.25 m/day
Temperature Correction (Arrhenius, $\theta = 1.06$)	$k_{25} = 0.335$ m/day at 25°C
Required Wetland Area (A)	24.7 ha (247,335 m ²)
Wetland Length × Width	861 m × 287 m (length-to-width ratio 3:1)
Media / Water Depth (d)	0.7 m
Hydraulic Retention Time (HRT)	2.0 days
Predicted BOD ₅ Removal Efficiency	> 91% (effluent BOD ₅ reduced to < 54 mg/L)
Design Equation	$A = (Q / k) \times \ln(C_0 / C_e)$

HSSF: horizontal subsurface flow; HRT: hydraulic retention time; ZEMA: Zambia Environmental Management Agency discharge limit.

The design predicts a BOD₅ removal efficiency exceeding 91%, reducing effluent BOD₅ from 600 mg/L to below 54 mg/L, approaching the ZEMA limit of 50 mg/L and representing a transformative improvement over current discharge quality. Additional BOD reduction through operational improvements at the WWTP itself would be expected to close the remaining gap to full compliance. This performance is well supported by field evidence from comparable tropical and subtropical systems. In Rwanda, Nsanzabaganwa et al. (2025) reported BOD removal efficiencies of 76-78% in HSSF-CWs treating municipal wastewater, with locally derived areal rate constants of 0.18-0.22 m/day. In Ethiopia, Angassa et al. (2020) documented 92% BOD₅ and 90.8% COD removal in a full-scale HSSF system treating domestic wastewater, while Berego et al. (2022) recorded significant

BOD and nutrient reductions in a constructed wetland planted with *Typha* and *Cyperus* under comparable tropical conditions. These findings confirm that the predicted performance of the HSSF-CW is realistic and achievable under Lusaka's climatic conditions, where warm dry-season temperatures (mean 25°C) enhance microbial activity and support higher areal rate constants than temperate systems.

The specified vegetation, *Phragmites australis*, is one of the most widely used and effective macrophyte species for HSSF-CWs, providing dense root networks that support biofilm development, improve hydraulic distribution, and facilitate nutrient uptake. Studies in Ethiopia (Engida et al., 2020) and Tanzania (Berego et al., 2022) have consistently demonstrated superior pollutant removal in planted versus unplanted wetland beds, validating its specification for this design. Additional co-benefits of the vegetated wetland would include partial nitrogen and phosphorus uptake, some pathogen reduction through filtration and UV exposure at the inlet zone, and ecological enhancement of the peri-urban environment.

3.4 Land Requirement, Sensitivity, and Feasibility Considerations

The 24.7-ha land requirement is the most significant feasibility constraint associated with this design. Because required area scales directly with the natural logarithm of the influent-to-target concentration ratio (Equation 1), it is sensitive to the choice of target effluent concentration. Table 4 illustrates this sensitivity by re-solving Equation 1 for alternative targets, holding all other design parameters constant.

Table 4. Sensitivity of required wetland area to target effluent BOD₅ concentration

Target Effluent BOD ₅ (mg/L)	Required Wetland Area (ha)	Change vs. ZEMA Design (%)
100 (relaxed interim target)	17.8	-28%
50 (ZEMA discharge standard – base design)	24.7	-
30 (matches Ngwerere upstream background)	29.8	+21%

Note: Areas computed using the same design flow ($Q = 33,300 \text{ m}^3/\text{day}$) and temperature-corrected rate constant ($k_t = 0.335 \text{ m/day}$) as the base design in Table 3.

A relaxed interim target of 100 mg/L, for example, as a first construction phase ahead of full ZEMA compliance, would reduce the land requirement by roughly 28%, while a stricter target matching upstream background quality (30 mg/L) would increase it by roughly 21%. This sensitivity underscores that a phased compliance target, combined with parallel improvements at the WWTP, could meaningfully de-risk land acquisition. In the context of peri-urban Lusaka, where urban expansion is

actively encroaching on available open land in the Manchinchi WWTP catchment, securing a contiguous 25-ha site would present a substantial planning and land acquisition challenge; a full engineering cost-benefit analysis would require site-specific land valuation, earthworks, and liner/media costing that fall outside the scope of the present study and are recommended as a priority for follow-on work. Qualitatively, the trade-off is between the near-zero energy and mechanical operating cost of a passive HSSF system against the opportunity cost of the land it occupies, a trade-off that favours phased or intensified configurations in land-constrained peri-urban settings.

Several strategies can address the land constraint. First, a phased or modular implementation approach, constructing the wetland in parallel treatment cells of 6-8 ha each, would distribute the spatial requirement and allow the system to be commissioned incrementally as land and funding become available; this also provides operational redundancy and facilitates maintenance. Second, intensified wetland configurations such as vertical flow constructed wetlands (VFCWs) or hybrid VF-HSSF systems can achieve comparable BOD removal efficiencies with significantly smaller footprints, due to enhanced oxygen transfer and higher volumetric treatment rates in VF systems (Fernandez-Fernandez et al., 2020). Forced-aeration intensified constructed wetlands (ICWs) have demonstrated BOD removal exceeding 90% in footprints 50-70% smaller than passive HSSF systems (Javeed et al., 2025), making them a technically viable alternative for space-constrained urban sites. Third, partial restoration of the existing WWTP's secondary treatment units, particularly the trickling filters, would substantially reduce the organic loading entering the CW, allowing a smaller wetland area to achieve the same effluent quality target.

Beyond treatment performance, the proposed hybrid system offers broader environmental and social value. The Ngwerere Stream serves downstream communities for informal irrigation and livestock watering; improving its water quality would directly benefit these users. The wetland itself would contribute to urban green infrastructure, providing amenity value and supporting biodiversity in an otherwise degraded peri-urban corridor. These co-benefits align with Zambia's Vision 2030 goals for inclusive and sustainable urban development and with NWASCO's mandate to promote environmentally responsible sanitation service delivery (NWASCO, 2018).

3.5 Study Limitations

Three limitations should be noted when interpreting these findings. First, water quality sampling was conducted exclusively during the dry season (May-October), specifically in October, the period of greatest pollutant concentration and lowest stream dilution; wet-season sampling is required to characterise seasonal variability in both WWTP performance and stream assimilative capacity. Second, the HSSF-CW design relies on a first-order areal rate constant ($k_{20} = 0.25$ m/day) drawn from published tropical and subtropical studies rather than site-specific pilot data; while conservative and consistent with comparable African case studies (Section 3.3), locally calibrated rate constants would reduce design uncertainty. Third, the design and sensitivity analysis (Section 3.4) address treatment performance and land area only; they do not incorporate capital cost, land valuation, or operation-and-

maintenance cost data, which were not available for this study and are recommended as a focus for follow-on feasibility work.

4. CONCLUSION AND POLICY RECOMMENDATIONS

This study assessed effluent quality from the Manchinchí Wastewater Treatment Plant, its impacts on the Ngwerere Stream, and the potential of a horizontal subsurface-flow constructed wetland as a polishing stage. The plant is performing below acceptable standards, with effluent BOD₅ at 600-629 mg/L and TSS at 769 mg/L, both far above ZEMA limits, mainly due to non-functional secondary treatment, hydraulic overloading, and inadequate maintenance. As a result, the Ngwerere Stream shows severe pollution, including near-zero dissolved oxygen downstream. A 24.7-ha HSSF constructed wetland, designed using a temperature-corrected first-order areal kinetic model, is predicted to achieve over 91% BOD₅ removal and reduce effluent BOD₅ to below 54 mg/L. With an HRT of about 2 days and *Phragmites australis* as the specified vegetation, the system offers a technically sound, low-energy polishing option; the main limitation is the large land requirement, for which modular construction, intensified wetland configurations, and WWTP restoration are recommended.

Policy Recommendations

- ZEMA discharge standard revisions: Consider a phased compliance pathway like an interim BOD₅ target above 50 mg/L) for hybrid WWTP-CW retrofits, recognising the land constraints demonstrated in Table 4, while maintaining a defined timeline to full compliance.
- LWSC operational improvements: Prioritise restoration of the Manchinchí WWTP's secondary treatment (trickling filters) and desludging schedule ahead of, or alongside, any constructed wetland investment, since reduced influent organic loading directly reduces the wetland area required.
- Zambia Vision 2030 sanitation targets: Position modular, nature-based polishing systems as a low-capital, low-energy complement to conventional WWTP upgrades in peri-urban catchments, consistent with inclusive and resource-efficient service delivery targets.
- NWASCO regulatory framework: Incorporate hybrid WWTP-CW performance monitoring (BOD₅, TSS, DO) into routine utility compliance reporting, and support pilot-scale validation of locally calibrated rate constants to reduce design uncertainty for future applications.

Overall, a hybrid system that combines conventional treatment with nature-based solutions provides a practical pathway to improving wastewater management in Lusaka and similar rapidly urbanising African cities, directly advancing the ZAWAFE 2026 call to accelerate integrated resilience solutions for Vision 2030 and the SDGs.

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