

Supplementary Information

Park-Integrated Vertical-Flow Constructed Wetlands for Reclaimed-Water Reuse in Riyadh: A Techno-Economic Screening and Decision Framework

This supplementary file is anonymized for double-blind review. The accompanying calculation workbook contains the same model inputs and formula-driven calculations used for the reported mass-balance and life-cycle-cost results.

S1. Evidence matrix

Evidence source	Context	System	Role in framework
KSU, Riyadh (Kamal 2023)	Hot-arid pilot	Three-stage SVFCW	Local climatic proof of concept; not municipal-scale validation
Oman full scale (Al-Wahaibi et al. 2021)	Hot-arid full scale	Two-stage VFCW with recirculation / process modification	Confirms strong aerobic treatment and nitrogen-management limitation
Saudi Red Sea (Ishtiaq et al. 2025)	Hot-arid large scale	VF-VF-HF hybrid	Saudi scale and operational precedent; hybrid nitrogen removal
Beijing Olympic Forest Park (Xie et al. 2012)	Public urban park	Integrated vertical-flow wetland	Public-landscape integration precedent
Baggiotto et al. 2025	Full-scale/research	Recirculation and partial saturation	Supports configurable total-N removal
Stefanakis et al. 2014	Design synthesis	Intermittent VFCWs	Hydraulic dosing, media, slope and oxygen-transfer screening basis

S2. Reference hydraulic design calculations

Reference flow $Q = 500 \text{ m}^3 \text{ d}^{-1}$; number of cells = 6; cell area = $20 \times 35 = 700 \text{ m}^2$; total active area $A = 4,200 \text{ m}^2$.

$HLR = Q/A = 500/4,200 = 0.119 \text{ m d}^{-1}$ (119 mm d^{-1}). Four doses d^{-1} were selected within the 3-10 doses d^{-1} range reported for intermittent VFCWs. The selected HLR is within the broader literature experience summarized in the main manuscript, but detailed design remains source-water and media dependent.

Condition	Active area	HLR	Volume per cell per dose	Pulse depth
Normal: 6 cells online	$4,200 \text{ m}^2$	0.119 m d^{-1}	20.83 m^3	29.8 mm
One cell offline	$3,500 \text{ m}^2$	0.143 m d^{-1}	25.00 m^3	35.7 mm

Conceptual filter depth is approximately 900 mm: 100 mm distribution gravel, 500 mm principal treatment media, 100 mm transition material and 200 mm drainage material above a protected 2 mm HDPE liner at approximately 1% base slope. Media gradation and hydraulic conductivity require site-specific testing.

S3. Water-balance screening

Wetland ET	ET loss	Net output	Recovery	Concentration factor
5 mm d^{-1}	$21 \text{ m}^3 \text{ d}^{-1}$	$479 \text{ m}^3 \text{ d}^{-1}$	95.8%	1.044
10 mm d^{-1} (base)	$42 \text{ m}^3 \text{ d}^{-1}$	$458 \text{ m}^3 \text{ d}^{-1}$	91.6%	1.092
15 mm d^{-1}	$63 \text{ m}^3 \text{ d}^{-1}$	$437 \text{ m}^3 \text{ d}^{-1}$	87.4%	1.144

The ET values are analytical screening assumptions. The 10 mm d^{-1} base case is intentionally conservative and is not a measured year-round Riyadh VFCW ET value. The associated $EC_{\text{out}} \approx EC_{\text{in}} \times \text{concentration-factor}$ relationship is only a conservative-solute screening approximation and is not a predictive irrigation-salinity model.

S4. Pollutant mass-balance results

$M = Q \times C / 1000$; removal duty = $(Q_{in} C_{in} - Q_{out} C_{target})/1000$. Nitrified ammonia is conservatively added to the nitrate load before denitrification screening.

Parameter	Case A	Case B	Case C
BOD ₅ removal, kg d ⁻¹	5.21	10.21	17.71
TSS removal, kg d ⁻¹	5.21	10.21	17.71
Ammonia-N removal, kg d ⁻¹	0.084	1.084	1.584
Direct nitrate reduction before nitrified NH ₃ , kg N d ⁻¹	0.336	2.336	8.836
Nitrate requiring denitrification after nitrification, kg N d ⁻¹	0.420	3.420	10.420
Theoretical minimum denitrification COD, kg d ⁻¹	1.20	9.78	29.80
PO ₄ removal, kg d ⁻¹	0.063	0.563	1.813
PO ₄ removal, kg yr ⁻¹	23.0	205.5	661.7

Phosphorus values are retained on the PO₄ reporting basis used in the Saudi standard; no conversion to elemental P or PO₄-P is applied.

S5. Aerobic capacity validation

The feasibility screen converts BOD₅ removal plus 4.3 times ammonium-N oxidation to an areal oxygen requirement. Literature summarized by Stefanakis et al. (2014) reports VFCW oxygen-transfer capacities of approximately 23-64 g O₂ m⁻² d⁻¹ in commonly cited systems and a broader range of about 7.9-156 g O₂ m⁻² d⁻¹.

Metric	Case A	Case B	Case C
BOD ₅ areal removal, g m ⁻² d ⁻¹	1.24	2.43	4.22
Ammonia-N areal removal, g N m ⁻² d ⁻¹	0.020	0.258	0.377
Screening O ₂ requirement, g O ₂ m ⁻² d ⁻¹	1.33	3.54	5.84
Selected literature comparator, g O ₂ m ⁻² d ⁻¹	23-64	23-64	23-64

All three calculated requirements are below the selected comparator. This is a screening check only: it supports the conclusion that aerobic polishing is unlikely to be the controlling process constraint at the reference area, but it does not replace kinetic design or guarantee field performance.

S6. Conceptual feasibility BOQ

Cost group	Quantity basis	Feasibility range	Status / next evidence
Earthworks / formation	~4,800 m ³	0.15-0.22 M SAR	Concept allowance; verify site quantities and local rates
Filter sand + graded gravel	~4,000 m ³	0.75-0.90 M SAR	Confirm local media gradation, quarry and transport
Liner + geotextile	~5,600 m ² liner	0.40-0.55 M SAR	Installed supplier quotation required
Distribution/drainage pipework	~2.7 km concept	0.30-0.40 M SAR	Final routing and installed rates required
Chambers/manifolds/valves	Allowance	0.15-0.22 M SAR	Engineering allowance; RFQ required

Cost group	Quantity basis	Feasibility range	Status / next evidence
EQ + treated-water storage	~550 m ³ effective	0.55-0.75 M SAR	Tank type and structural basis to be confirmed
Pumps/MCC/control	Allowance	0.15-0.22 M SAR	Duty/head and controls to be detailed
Filtration/disinfection	Allowance	0.12-0.20 M SAR	Compliance package; pathogen model not included
Instrumentation	Allowance	0.10-0.15 M SAR	Monitoring scope to be confirmed
Wetland planting/establishment	4,200 m ²	0.12-0.20 M SAR	Species and establishment plan required

These quantities and costs are planning-level feasibility estimates, not tender rates. GASTAT construction-price information is used only as calibration context. Supplier quotations and installed unit rates should replace allowance items before an investment decision. Land purchase is excluded from the base case and land opportunity cost is treated separately.

S7. Economic model, renewal sensitivity and break-even rule

Base economic assumptions: 30-year analysis period; 6% real discount rate; 95% availability; annual treated volume 173,375 m³ yr⁻¹; base delivered volume 158,811.5 m³ yr⁻¹; common upstream treatment and existing sunk infrastructure excluded.

Indicator	Case A	Case B	Case C
CAPEX, M SAR	3.3-4.2	3.8-5.3	4.8-6.7
Mature OPEX, SAR m ⁻³ treated	0.50-0.70	0.75-1.05	1.30-1.90
30-y NPC, M SAR	4.49-5.87	5.59-7.81	7.90-11.23
Midpoint NPC, M SAR	5.18	6.70	9.57
Delivered-water LC, SAR m ⁻³	2.06-2.69	2.56-3.57	3.61-5.14
Midpoint delivered LC, SAR m ⁻³	2.37	3.06	4.38
10% CAPEX renewal reserve at year 15, SAR m ⁻³	0.07	0.09	0.11
Midpoint LC incl. reserve sensitivity, SAR m ⁻³	2.44	3.15	4.49

The base NPC model includes CAPEX plus annual OPEX and does not include a discrete major-equipment replacement event because supplier-specific service lives were not available. The 10% CAPEX year-15 reserve shown above is therefore presented as a renewal sensitivity, not as a prediction of replacement requirements.

Economic preference is evaluated using the same incremental boundary: GO when LC_PWH < LC_conventional, incremental. The site-specific break-even last-mile cost is C_last-mile, BE = LC_PWH – C_central, incremental polishing. No universal pipeline-distance threshold is assigned.

S8. Case B sensitivity

Variable	Low	Base	High	Delivered LC at low	Delivered LC at high
ET, mm d ⁻¹	5	10	15	2.93	3.21
CAPEX multiplier	0.70	1.00	1.30	2.44	3.69
OPEX multiplier	0.70	1.00	1.30	2.77	3.36
Discount rate	3%	6%	9%	2.44	3.77
Project life, y	20	30	40	3.48	2.89

Sensitivity values are in SAR m⁻³ delivered for the Case B midpoint. Source-water class is treated as a separate scenario dimension rather than as a one-factor sensitivity because it changes process architecture as well as cost.

S9. Recommended pilot monitoring

A future Riyadh pilot should operate for at least one complete annual climatic cycle. Minimum monitoring should include influent and effluent flow, temperature, EC, TDS, pH, dissolved oxygen, turbidity, BOD₅, COD, TSS, ammonia-N, nitrate-N, total nitrogen, phosphorus, microbiological indicators, evapotranspiration/water balance, energy consumption, infiltration capacity, maintenance interventions, chemical consumption, media condition, vegetation performance, odor and mosquito risk. Hydraulic infiltration decline should be treated as a key long-term performance indicator, not only effluent quality.

S10. Reproducibility resource

The accompanying file JKSES_VFCW_Calculation_Workbook.xlsx contains formula-driven versions of the principal inputs, source-water cases, water and pollutant mass balances, aerobic-capacity check, life-cycle-cost model, sensitivity calculations and conceptual BOQ. It is intended to allow reviewers to reproduce the reported screening results and to substitute site-specific inputs when available.