

Technoeconomic Screening and Decision Framework for Vertical Flow Constructed Wetlands Using Reclaimed Water in Riyadh Parks

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Research Article

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Abstract

Rapid urban greening in hot-arid cities increases non-potable irrigation demand while making the last-mile delivery of reclaimed water an important infrastructure question. This study evaluates a park-integrated vertical-flow constructed wetland (VFCW) as a decentralized polishing unit within Riyadh's reclaimed-water system. A 500 m³ d⁻¹ reference Park Water Hub was assessed using hydraulic sizing, pollutant mass balances, an oxygen-demand capacity check, evapotranspiration-adjusted water recovery and 30-year life-cycle costing. Three analytical source-water cases were examined: low-strength reclaimed water, intermediate secondary effluent and a regulatory upper-bound secondary-effluent case. The reference design uses six parallel cells with 4,200 m² active area, a hydraulic loading rate of 0.119 m d⁻¹ and four intermittent doses per day. Calculated aerobic oxygen requirements were 1.33–5.84 g O₂ m⁻² d⁻¹, below reported VFCW oxygen-transfer capacities, indicating that nutrient removal rather than aerobic polishing controls the treatment boundary. Under a 10 mm d⁻¹ annualized screening ET assumption, 91.6% of influent water remains available for irrigation. Modelled midpoint delivered-water costs are 2.37, 3.06 and 4.38 SAR m⁻³. The framework therefore treats source-water quality, salinity, land availability and the incremental cost of the conventional reclaimed-water pathway as explicit GO/NO-GO variables. Park-integrated VFCWs are proposed as selective complements to centralized reuse networks, not universal substitutes.

1. Introduction

Urban greening in hot-arid regions creates a structural water-management challenge. Large-scale tree planting, public-park development and streetscape greening generate sustained irrigation demand in environments where potable water should not be the primary irrigation source. Riyadh is a relevant case because major greening programmes are developing alongside expansion of treated-wastewater reuse infrastructure (RCRC 2024). The long-term challenge is therefore not limited to producing reclaimed water at centralized treatment plants, but also includes delivering water of suitable quality to dispersed landscapes at an acceptable whole-life cost.

Centralized wastewater treatment offers economies of scale, but the marginal cost of serving an individual park may include conveyance pipelines, road crossings, pumping, intermediate storage, utility diversions and local distribution infrastructure. Reviews of wastewater infrastructure planning increasingly describe hybrid systems in which centralized treatment is combined with decentralized or satellite reuse where local conditions justify it (Pasciucco et al. 2022; Prateep Na Talang et al. 2022). A low treatment tariff alone therefore does not represent the full incremental cost of supplying reclaimed water to a particular landscape.

Vertical-flow constructed wetlands treat wastewater by intermittent loading over a porous planted bed followed by vertical percolation and gravity drainage. Drainage between doses promotes atmospheric air entry, supporting organic-matter oxidation and nitrification (Stefanakis et al. 2014). Their relatively compact footprint compared with horizontal-flow wetlands is attractive for urban applications, but

nitrogen and phosphorus removal remain configuration-dependent and long-term performance can be constrained by clogging, substrate properties and hydraulic distribution (Fang et al. 2022; Mishra et al. 2024; Wu et al. 2023).

Hot-arid and Saudi evidence indicates that the technology is technically plausible but application-specific. A small VFCW pilot has been reported at King Saud University in Riyadh (Kamal 2023). A full-scale two-stage VFCW in Oman achieved strong organic, solids and ammonium removal, while total-nitrogen performance required operational modification and carbon management (Al-Wahaibi et al. 2021). A much larger hybrid wetland system in the Saudi Red Sea region has reported successful staged vertical- and horizontal-flow operation with recirculation and step-feeding (Ishtiaq et al. 2025). Saudi and regional reviews similarly identify constructed wetlands as promising under hot-arid conditions while emphasizing land, salinity, nutrient removal and long-term operation as design constraints (Alnaser et al. 2023; Stefanakis 2020).

The Park Water Hub evaluated here does not receive raw sewage. It starts with secondary or reclaimed water and provides local polishing, conditional nutrient removal, disinfection, storage and irrigation supply. The research question is: under what combinations of source-water quality, available park area, irrigation demand and incremental conventional infrastructure cost does a park-integrated VFCW become a technically and economically credible option for Riyadh? The contribution is an application-boundary framework that links process capacity, hot-arid water recovery, salinity and same-boundary life-cycle cost rather than proposing a new wetland treatment mechanism. Figure 1 summarizes the system boundary and the two incremental pathways compared.

2. Literature Review

2.1 VFCW treatment fundamentals

Intermittently loaded VFCWs promote oxygen transfer as the bed drains and air is drawn into pore spaces between dosing events. Typical configurations use graded sand and gravel, surface distribution, bottom drainage, a liner and emergent vegetation. Reported bed depths are approximately 0.45–1.20 m, and bottom slopes of about 1–2% are commonly used to support drainage (Stefanakis et al. 2014).

The aerobic character that favours nitrification does not by itself guarantee low total nitrogen. Nitrified ammonium remains as nitrate unless an oxygen-limited zone and sufficient biodegradable carbon support denitrification. Recirculation, partial saturation, step-feeding, anoxic polishing or hybrid horizontal-flow stages can therefore be required (Al-Wahaibi et al. 2021; Baggiotto et al. 2025; Wu et al. 2023).

Phosphorus removal depends on filtration, adsorption and precipitation and is strongly affected by media mineralogy and finite sorption capacity. Clogging is similarly a long-term hydraulic risk driven by solids accumulation, biofilm growth, media properties, loading and distribution. Recent reviews

emphasize monitoring hydraulic conductivity or infiltration performance and maintaining practical rehabilitation options (Fang et al. 2022; Mishra et al. 2024).

2.2 Hot-arid, Saudi and public-landscape evidence

Hot-arid climates do not preclude biological treatment, but they strengthen the need to account for water loss and salinity. Riyadh climate studies report high evaporative demand, with strong seasonal variation (El-Rawy et al. 2023). For this reason, wetland ET is treated in this paper as a screened water-balance variable rather than a fixed biological design constant.

At KSU in Riyadh, a three-stage pilot SVFCW treating institutional wastewater was monitored for 28 days and reported substantial BOD, COD, TSS and ammonia-N removal (Kamal 2023). The short duration and small reactor dimensions prevent direct municipal-scale extrapolation, but the study provides local climatic proof of concept. In Oman, a full-scale two-stage VFCW treated approximately $50 \text{ m}^3 \text{ d}^{-1}$ over 18 months; nitrate and total-N targets required step-feeding and external carbon addition (Al-Wahaibi et al. 2021). The Red Sea system provides a stronger Saudi scale precedent through a large VF-VF-HF hybrid system designed for phased expansion and optimized using recirculation and step-feeding (Ishtiaq et al. 2025). A separate Riyadh design study has also evaluated horizontal subsurface-flow constructed wetlands for decentralized wastewater reuse, reinforcing local interest in nature-based treatment while representing a different wetland configuration (Gabr et al. 2023).

Public-landscape integration has also been demonstrated internationally. The integrated vertical-flow wetland in Beijing Olympic Forest Park occupies approximately $45,000 \text{ m}^2$ and treats reclaimed wastewater and recirculated lake water (Xie et al. 2012). This precedent supports physical integration into a major public landscape, but its climatic and social context is not assumed to transfer directly to Riyadh.

2.3 Research gap and decision framing

Within the literature reviewed for this study, comparatively few publications combine VFCW process sizing with a same-boundary economic comparison against the incremental infrastructure needed to deliver reclaimed water to dispersed urban irrigation points. Research on centralization level and decentralized reuse shows that treatment scale, conveyance, local reuse demand and system boundaries materially affect the preferred configuration (López-Serrano et al. 2023; Pasciucco et al. 2022; Prateep Na Talang et al. 2022). This study therefore focuses on when local polishing is appropriate, rather than whether constructed wetlands can treat wastewater in principle.

3. Materials and Methods

3.1 Study boundary and reference system

A planning-level techno-economic model was developed for a $500 \text{ m}^3 \text{ d}^{-1}$ Park Water Hub receiving secondary or reclaimed water and producing water for landscape irrigation. The study boundary includes

equalization, VFCW treatment, source-dependent nutrient polishing, final filtration/disinfection, treated-water storage, pumps, pipework and controls. Upstream wastewater treatment common to both alternatives and existing sunk infrastructure are excluded.

The reference economic period is 30 years, with a 6% real discount rate and 95% annual availability. Land purchase is excluded from the base case because the system is assumed to occupy publicly controlled landscape land; land opportunity cost is evaluated separately as a site gate and sensitivity variable.

3.2 Saudi criteria and analytical source-water cases

The current Saudi Standards and Specifications for Treated Wastewater distinguish between treated-water production standards and reuse criteria (MEWA 2025). Internal study targets were set below selected tertiary reuse values to provide operational margin; they are design targets, not regulatory limits.

The Saudi treated-wastewater criteria and internal design targets applied in this study are summarized in Table 1.

Table 1
Saudi treated-wastewater criteria used in the study and internal design targets (MEWA 2025).

Parameter	Secondary production	Tertiary production	Tertiary reuse	Internal target
TSS, mg/L	40	10	10 monthly; 15 max	≤ 5
BOD ₅ , mg/L	40	10	10 monthly; 15 max	≤ 5
COD, mg/L	90	50	50	—
Turbidity, NTU	5	5	5	—
NO ₃ -N, mg/L	25	10	10	≤ 8
Ammonia-N, mg/L	5	5	5	≤ 2
PO ₄ , mg/L	≤ 5	≤ 2	≤ 2	≤ 1.5
Free residual Cl ₂ , mg/L	> 0.5	> 0.5	0.2–0.5	Regulatory control
Fecal coliform, /100 mL	1000	2.2	2.2	Regulatory control
Helminth eggs, /L	1	0	0	Regulatory control

Microbiological compliance is treated as a mandatory downstream design constraint. The mass-balance model does not predict pathogen removal by the VFCW; final filtration/disinfection and verification

monitoring must achieve the applicable reuse criteria.

Three analytical source-water cases were defined: Case A, low-strength reclaimed water; Case B, intermediate secondary effluent; and Case C, a regulatory upper-bound secondary-effluent case. Cases A and B are study assumptions, not measurements from specific Riyadh plants. Case C approximates the current Saudi secondary-production upper limits for the parameters examined (MEWA 2025).

3.3 Hydraulic design basis and dosing

The reference system consists of six parallel VFCW cells, each 20 × 35 m (700 m²), for 4,200 m² active area. At 500 m³ d⁻¹, the hydraulic loading rate (HLR) is 0.119 m d⁻¹ (119 mm d⁻¹). Four dosing cycles per day were selected within the 3–10 doses d⁻¹ range reported for intermittent VFCWs, allowing drainage and reaeration between batches (Stefanakis et al. 2014). Literature summarized by Stefanakis et al. (2014) reports good nitrification at hydraulic loads up to 180 mm d⁻¹ and a more conservative 100 mm d⁻¹ recommendation for full nitrification in higher-strength domestic wastewater. Because the present application is polishing lower-ammonia water, an explicit oxygen-demand capacity check was added rather than treating HLR alone as proof of capacity.

Four doses per day give 20.83 m³ per cell per pulse, equivalent to 29.8 mm. With one cell offline, active area falls to 3,500 m², HLR rises to 0.143 m d⁻¹ and pulse depth to 35.7 mm. The conceptual section uses approximately 900 mm total media: 100 mm distribution gravel, 500 mm principal treatment media, 100 mm transition media and 200 mm drainage material over a protected 2 mm HDPE liner at approximately 1% base slope. Final gradation and hydraulic conductivity require site-specific sieve and permeability testing. The reference process train and conceptual VFCW cross-section are shown in Figs. 2 and 3.

3.4 Water, salinity and pollutant mass balances

Wetland evapotranspiration (ET) was included because water recovery is a primary design concern in Riyadh. Screening values of 5, 10 and 15 mm d⁻¹ were evaluated over the 4,200 m² active area. The 10 mm d⁻¹ base case is intentionally conservative as an annualized wetland screening assumption; it is not presented as measured year-round VFCW ET. Published Riyadh climate data show substantial evaporative demand but lower mean reference ET than this screening value, reinforcing the need for pilot measurement (El-Rawy et al. 2023).

$$Q_{ET} = ET_{wet} \times A_{wet} / 1000$$

1

$$Q_{out} = Q_{in} - Q_{ET}$$

2

$$CF = Q_{in} / Q_{out}$$

For conservative dissolved constituents, $EC_{out} \approx EC_{in} \times CF$ was used only as a first-order concentration screening approximation. It is not a predictive salinity model and does not account for precipitation, ion exchange, plant uptake or irrigation-soil interactions.

$$M_{rem} = (Q_{in} C_{in} - Q_{out} C_{target}) / 1000$$

where M_{rem} is in $kg\ d^{-1}$ for Q in $m^3\ d^{-1}$ and C in $mg\ L^{-1}$. Nitrified ammonia was conservatively added to nitrate before denitrification screening. A theoretical minimum of 2.86 g COD per g NO_3 -N removed was used for carbon-demand screening (Tchobanoglous et al. 2014). Phosphorus balances were retained on the PO_4 reporting basis used in the Saudi standard.

3.5 Aerobic capacity screening

The aerobic load was screened using the oxygen-transfer expression summarized for VFCWs by Stefanakis et al. (2014), in which BOD_5 removal and ammonium oxidation are converted to an areal oxygen requirement. This check is intended to test whether the selected 4,200 m^2 area is obviously oxygen-limited; it does not replace detailed kinetic design.

$$O_{req} = 1000(M_{BOD5,rem} + 4.3 M_{NH4-N,rem}) / A$$

In Eq. (5), $M_{BOD5,rem}$ and $M_{NH4-N,rem}$ are the ET-adjusted removal duties in $kg\ d^{-1}$, A is active VFCW area in m^2 , and the factor 1000 converts $kg\ d^{-1}$ to $g\ d^{-1}$.

Reported VFCW oxygen-transfer capacities summarized in the same reference span approximately 23–64 $g\ O_2\ m^{-2}\ d^{-1}$ in commonly cited systems, with a broader literature range of about 7.9–156 $g\ O_2\ m^{-2}\ d^{-1}$. Calculated requirements were compared against these reported ranges as a feasibility screen.

3.6 Economic model and decision rule

Capital cost was developed from a quantity-based conceptual bill of quantities for the 500 $m^3\ d^{-1}$ reference system using recent Saudi construction-price information as calibration context (GASTAT 2026). Items without robust public installed unit rates were retained as engineering allowances and tested at $\pm 30\%$. The estimate is therefore suitable for feasibility comparison, not tendering. Base life-cycle cost does not include a discrete major-equipment replacement event because supplier-specific service lives were not available; this is treated as a limitation and a separate renewal-reserve sensitivity in the Supplementary Information.

$$NPC = CAPEX + \sum_{t=1}^n [OPEX_t / (1 + r)^t]$$

$$LC_{delivered} = NPC / \sum_{t=1}^n [V_{out,t} / (1 + r)^t]$$

Economic alternatives were compared using the same incremental system boundary. The conventional pathway comprises any additional centralized polishing required to achieve the target reuse quality plus marginal conveyance, pumping, storage and site-connection infrastructure. The decentralized pathway comprises the complete Park Water Hub. Common upstream treatment is excluded from both.

$$GO \text{ if } LC_{PWH} < LC_{conventional, incremental}$$

$$C_{last-mile, BE} = LC_{PWH} - C_{central, incremental polishing}$$

Equation (9) expresses the site-specific break-even condition without assuming a universal pipeline distance. If the independently estimated incremental centralized polishing cost is known, the difference gives the maximum levelized last-mile cost at which the conventional pathway remains competitive.

Sensitivity analysis varied ET (5–15 mm d⁻¹), CAPEX and OPEX (± 30%), discount rate (3–9%), project life (20–40 years), hydraulic loading and site-dependent marginal network cost.

Detailed evidence tables, design calculations, the conceptual BOQ, economic assumptions and sensitivity results are provided in Online Resource 1; the formula-driven calculation workbook used to reproduce the reported results is provided in Online Resource 2.

3.7 Use of AI-assisted tools

Generative AI-assisted tools (OpenAI ChatGPT) were used during manuscript development for literature organization, drafting support, language editing, consistency checks and document formatting. All engineering assumptions, calculations, source verification, interpretation and final wording were reviewed and approved by the author, who takes full responsibility for the content and integrity of the manuscript.

4. Results

4.1 Water recovery and source-water cases

At the 10 mm d⁻¹ base ET assumption, the 4,200 m² wetland loses 42 m³ d⁻¹, leaving 458 m³ d⁻¹ for irrigation, equivalent to 91.6% recovery. The corresponding first-order concentration factor is 1.092. At 5 and 15 mm d⁻¹, recovery is 95.8% and 87.4%, respectively.

The analytical source-water assumptions and calculated treatment duties are summarized in Table 2.

Table 2
Analytical source-water assumptions and calculated treatment duties.

Input / result	Case A	Case B	Case C
Source-water description	Low-strength reclaimed	Intermediate secondary	Regulatory upper-bound secondary
BOD ₅ influent, mg/L	15	25	40
COD influent, mg/L	45	65	90
TSS influent, mg/L	15	25	40
Ammonia-N influent, mg/L	2	4	5
NO ₃ -N influent, mg/L	8	12	25
PO ₄ influent, mg/L	1.5	2.5	5
BOD ₅ removal, kg/d	5.21	10.21	17.71
TSS removal, kg/d	5.21	10.21	17.71
Ammonia-N removal, kg/d	0.084	1.084	1.584
NO ₃ -N requiring denitrification after nitrification, kg N/d	0.42	3.42	10.42
Theoretical minimum denitrification COD, kg/d	1.20	9.78	29.8
PO ₄ removal, kg/d	0.063	0.563	1.813
Indicative process architecture	VFCW + disinfection	VFCW + limited N/P polishing	Full hybrid polishing

4.2 Aerobic capacity validation

The aerobic capacity screening results for the three analytical cases are summarized in Table 3.

Table 3

Aerobic capacity screening. Literature comparator from Stefanakis et al. (2014); reported values extend beyond 23–64 g O₂ m⁻² d⁻¹ in some systems.

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 oxygen requirement, g O ₂ m ⁻² d ⁻¹	1.33	3.54	5.84
Reported VFCW oxygen-transfer capacity used for comparison	23–64 g O ₂ m ⁻² d ⁻¹	23–64 g O ₂ m ⁻² d ⁻¹	23–64 g O ₂ m ⁻² d ⁻¹

Calculated oxygen requirements are below the lower end of the selected literature comparator in all three cases. On this screening basis, conventional aerobic BOD and ammonium polishing is not the controlling capacity constraint for the 4,200 m² reference bed. The result does not guarantee performance because actual oxygen transfer depends on media, dosing uniformity, drainage, temperature and clogging; it instead supports focusing the design boundary on nitrate, phosphorus and hydraulics.

4.3 Nitrogen and phosphorus define the treatment boundary

After accounting for ammonia nitrification, nitrate-N requiring denitrification increases from 0.42 kg N d⁻¹ in Case A to 10.42 kg N d⁻¹ in Case C. The corresponding theoretical minimum carbon demand rises from 1.20 to 29.8 kg COD d⁻¹. Enlarging the aerobic VFCW alone therefore does not resolve the upper-bound case; a dedicated anoxic function, step-feeding/recirculation strategy or equivalent hybrid configuration is required.

PO₄ removal increases from 0.063 to 1.813 kg d⁻¹, equivalent to approximately 23 to 662 kg yr⁻¹ on the reported PO₄ basis. Because phosphorus sorption capacity is finite, higher-loading cases require defined reactive-media inventory, replacement planning and renewed economic assessment rather than a single permanently oversized phosphorus stage.

4.4 Life-cycle cost, thresholds and sensitivity

Table 4

Planning-level economic results and direct incremental break-even thresholds. Assumptions: 30-year horizon, 6% real discount rate, 95% availability and base water-recovery case.

Economic 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
Conventional incremental LC required to beat midpoint PWH, SAR/m ³	> 2.37	> 3.06	> 4.38

For the Case B midpoint (3.06 SAR m⁻³), CAPEX ± 30% produces an approximate delivered-cost range of 2.44–3.69 SAR m⁻³; discount rate 3–9% gives 2.44–3.77 SAR m⁻³; OPEX ± 30% gives 2.77–3.36 SAR m⁻³; and project life 20–40 years gives 2.89–3.48 SAR m⁻³. ET variation from 5 to 15 mm d⁻¹ produces a

smaller cost effect (approximately 2.93–3.21 SAR m⁻³) but a material water-recovery and salinity effect. A 10% mid-life CAPEX renewal reserve at year 15 would add approximately 0.07, 0.09 and 0.11 SAR m⁻³ to the midpoint costs of Cases A-C, respectively; this is presented as sensitivity rather than included in the base model. Figure 4 summarizes the main case-dependent treatment duties and midpoint delivered-water life-cycle costs.

4.5 Application boundary

The strongest application is a site with relatively good secondary or reclaimed water, low-to-moderate nutrient concentrations, sufficient park land, substantial irrigation demand and a high incremental cost for the conventional reclaimed-water connection. The weakest application is nutrient-rich secondary effluent where compliant TSE is already available at low incremental cost. No universal break-even distance is assigned because pipe diameter, crossings, pumping head, storage and urban constraints are site-specific. Instead, Table 4 gives the levelized conventional-cost threshold that must be exceeded for the Park Water Hub to be economically preferred.

5. Discussion

The added oxygen-demand screen strengthens the central process finding: at the reference area, aerobic BOD and ammonia polishing is not the dominant feasibility constraint. Source-water quality determines whether the Park Water Hub can remain a relatively simple VFCW-led polishing system or must evolve into a more complex hybrid plant. This interpretation is consistent with hot-arid full-scale experience in Oman and Saudi Arabia and with broader constructed-wetland literature showing that nitrogen removal frequently requires process intensification beyond a simple aerobic VF stage (Al-Wahaibi et al. 2021; Ishtiaq et al. 2025; Wu et al. 2023).

Source selection is therefore more important than simply maximizing wetland size. Case A represents the preferred application envelope because the wetland mainly performs polishing and quality assurance. Case C requires enough nitrogen and phosphorus treatment to remove much of the low-complexity advantage that motivates a park-based system.

Hot-arid conditions create a water-balance and salinity problem rather than an inherent biological prohibition. Under the conservative base screening assumption, 91.6% of influent remains available for irrigation, while conservative dissolved constituents could concentrate by about 9%. A treatment train could therefore satisfy BOD, solids and nutrient criteria and still fail agronomic suitability if EC, TDS or SAR are excessive. Site-specific salinity monitoring and soil/plant compatibility are mandatory design gates.

Economically, the relevant comparison is not the total tariff of a large centralized sewage-treatment plant. The correct comparator is the incremental conventional pathway needed to serve the same irrigation demand. The levelized thresholds in Table 4 make that criterion explicit. This same-boundary framing is consistent with research showing that optimal centralization depends on network, scale, local

reuse demand and distribution cost rather than treatment cost alone (López-Serrano et al. 2023; Pasciucco et al. 2022; Prateep Na Talang et al. 2022).

Land remains a constraint even where acquisition cost is avoided. A park-integrated VFCW occupies space that could otherwise support recreation, planting or other programme uses. Visible planted cells can be integrated with the landscape, but hydraulically critical and public-health components should remain secure and maintainable. Large trees should generally remain outside the filter media to protect distribution systems, drainage, liner integrity and rehabilitation access.

A multi-cell layout is also a maintenance strategy. Clogging cannot be predicted from solids loading alone and remains a major life-cycle risk in subsurface-flow wetlands (Fang et al. 2022; Mishra et al. 2024). Cell isolation allows resting, inspection and rehabilitation while other cells remain available. A pilot should therefore monitor infiltration decline as well as effluent quality.

The $500 \text{ m}^3 \text{ d}^{-1}$ reference scale is a functional unit, not a requirement for every park. District-scale hubs serving several parks, street-tree corridors or civic landscapes may improve economy of scale while reducing the number of treatment and monitoring locations. GIS-based spatial optimization is therefore a logical next stage for Riyadh.

5.1 Limitations and validation needs

Cases A and B are analytical source-water cases rather than measured year-round datasets from specific Riyadh facilities. The ET range is a screening assumption, not a measured annual Riyadh VFCW record. The cost model is feasibility-grade and several items remain engineering allowances pending supplier quotations. Installed unit rates, major-equipment service lives and a site-specific Riyadh TSE connection BOQ were not available. The framework therefore defines the decision criterion and screening thresholds rather than proving a specific site is economical.

Long-term Riyadh-specific evidence on clogging, salinity accumulation, media life and maintenance remains limited. The Saudi standard reports phosphorus as PO_4 , and the exact reporting basis should be confirmed with the competent authority before detailed process design. The microbiological stage is represented as a compliance requirement rather than a pathogen-removal model. These limitations require pilot validation and detailed design before investment decision-making.

6. Conclusions and Recommendations

This study developed a techno-economic screening and decision framework for park-integrated VFCWs as decentralized reclaimed-water polishing infrastructure in Riyadh. The reference $500 \text{ m}^3 \text{ d}^{-1}$ configuration uses $4,200 \text{ m}^2$ active VFCW area at 119 mm d^{-1} HLR. A screening oxygen-demand check produced requirements of $1.33\text{--}5.84 \text{ g O}_2 \text{ m}^{-2} \text{ d}^{-1}$, below reported VFCW oxygen-transfer capacities, supporting the conclusion that conventional aerobic polishing is not the principal process constraint under the stated assumptions.

The controlling treatment variable is source-water nutrient quality, particularly nitrate and phosphorus. The low-strength case can remain VFCW-led, whereas the regulatory upper-bound secondary-effluent case requires sufficient denitrification and phosphorus management to move the concept toward a more complex hybrid facility.

At the conservative 10 mm d⁻¹ annualized ET screening assumption, 91.6% of influent remains available for irrigation. ET is not the dominant life-cycle cost driver in the tested range, but it affects water recovery and provides a direct reason to treat salinity as a mandatory site gate.

Modelled midpoint delivered-water costs are 2.37, 3.06 and 4.38 SAR m⁻³ for Cases A-C. These values do not demonstrate that decentralized treatment is universally cheaper. The Park Water Hub becomes economically preferred only when the levelized incremental conventional pathway serving the same demand exceeds the corresponding scenario cost, after common upstream treatment is excluded from both alternatives.

Implementation should proceed through: (i) GIS screening of parks, irrigation demand, water sources, TSE infrastructure, topography and urban constraints; (ii) seasonal source-water characterization including nutrients and salinity; and (iii) a 500 m³ d⁻¹ demonstration operated for at least one full climatic year. Success should require simultaneous regulatory compliance, hydraulic reliability, acceptable irrigation salinity, manageable maintenance and a site-specific economic advantage over the conventional incremental pathway. The resulting screening sequence is summarized in Fig. 5.

The GO/NO-GO screening framework for park-integrated VFCWs is summarized in Table 5.

Table 5
GO/NO-GO screening framework for park-integrated VFCWs.

Decision gate	GO condition	If not satisfied
1. Local water source	Reliable secondary/reclaimed source at required flow	Conventional supply or alternative source
2. Source quality	N/P and other contaminants treatable without excessive complexity	Full hybrid treatment and economic reassessment
3. Regulatory compliance	Final reuse quality achievable with reliable disinfection	Upgrade treatment architecture
4. Available land	Area sufficient for cells, storage, access and polishing	Compact treatment or conventional TSE
5. Water recovery	Seasonal recovery adequate for irrigation demand	Increase source flow / redesign
6. Salinity	EC/TDS/SAR compatible with soil and planting	Alternative source, blending or NO-GO
7. Public integration	Secure service access, separation and maintainability	Redesign or alternative site
8. Economics	$LC_{PWH} < LC_{conventional, incremental}$	Conventional pathway preferred
9. Cluster opportunity	Hub can beneficially serve nearby demands	Assess individual-site solution

Declarations

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Author Contribution

S.A. conceived and designed the study, developed the methodology, conducted the data collection and analysis, interpreted the findings, prepared the figures and tables, and wrote, reviewed, and edited the manuscript. S.A. read and approved the final manuscript.

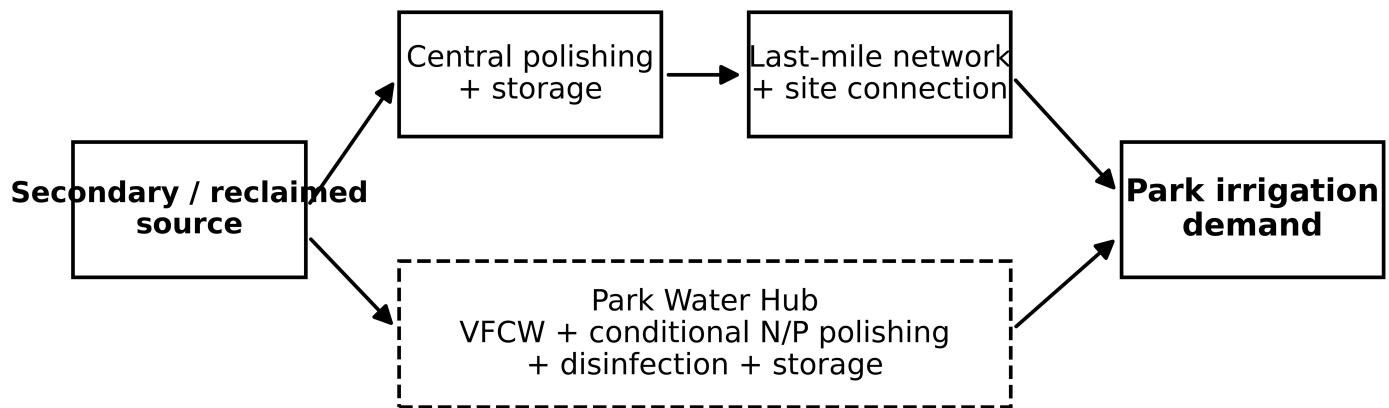
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Figures

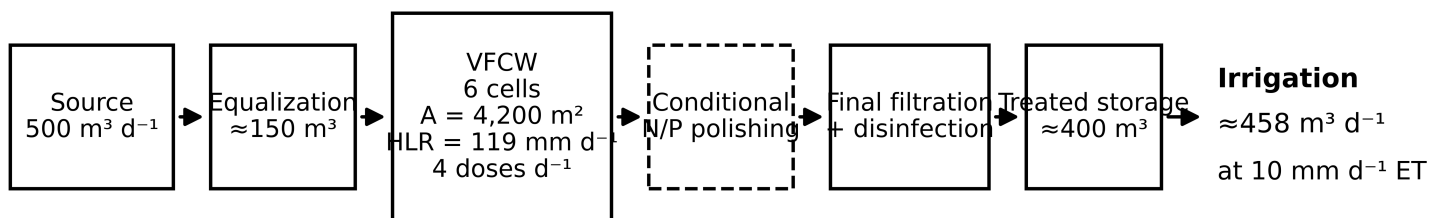
Common upstream treatment is outside the incremental comparison



Compare only the additional pathway required to serve the same irrigation demand

Figure 1

System boundary for the incremental comparison. Common upstream treatment is excluded from both pathways; the comparison is between the Park Water Hub and the additional centralized polishing and last-mile infrastructure required to serve the same irrigation demand



Dashed stage is source-water dependent; reuse compliance is verified after final disinfection

Figure 2

Process train for the 500 m³ d⁻¹ reference Park Water Hub. The dashed nutrient-polishing stage is source-water dependent; treated-water output is approximately 458 m³ d⁻¹ under the 10 mm d⁻¹ ET screening case

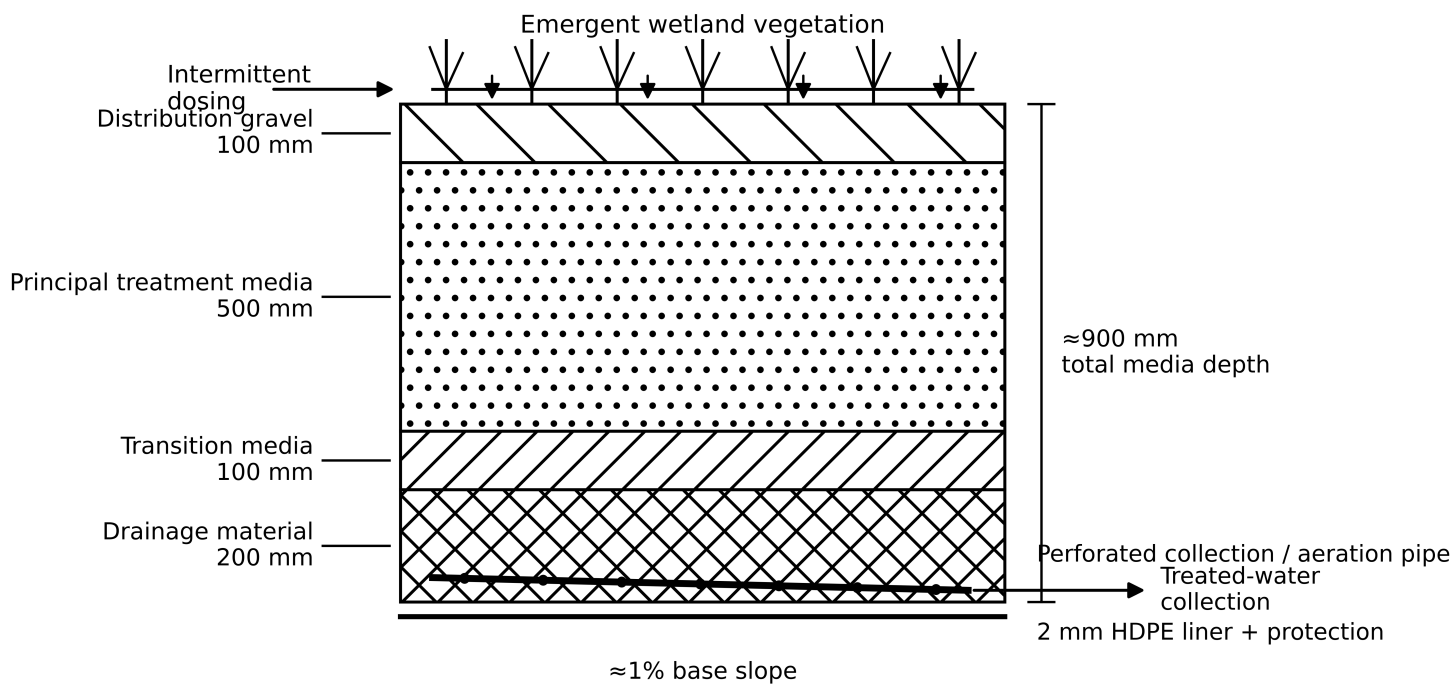


Figure 3

Reference cross-section of a VFCW cell used in the feasibility design. Layer thicknesses are conceptual; final media gradation and hydraulic conductivity require site-specific sieve and permeability testing

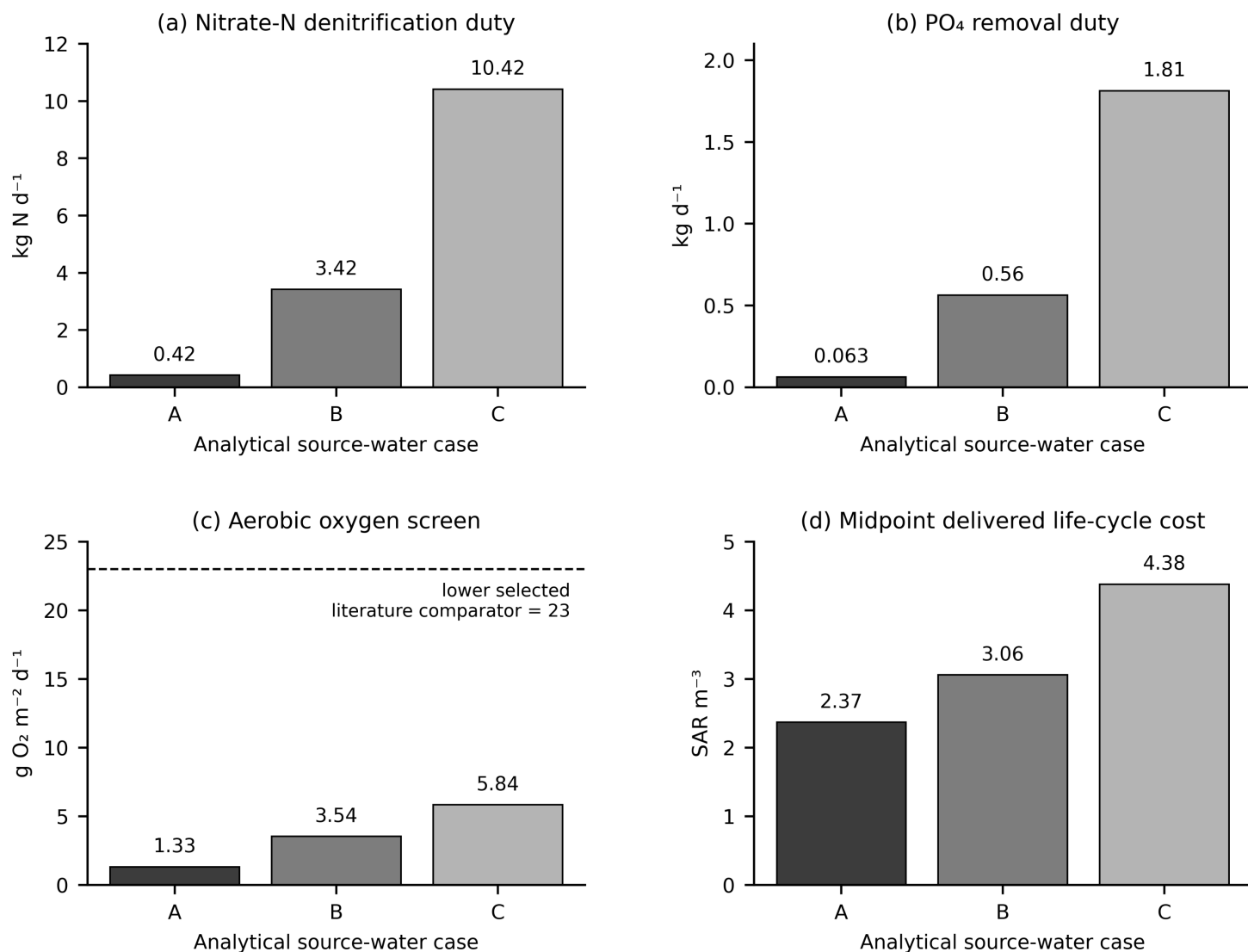
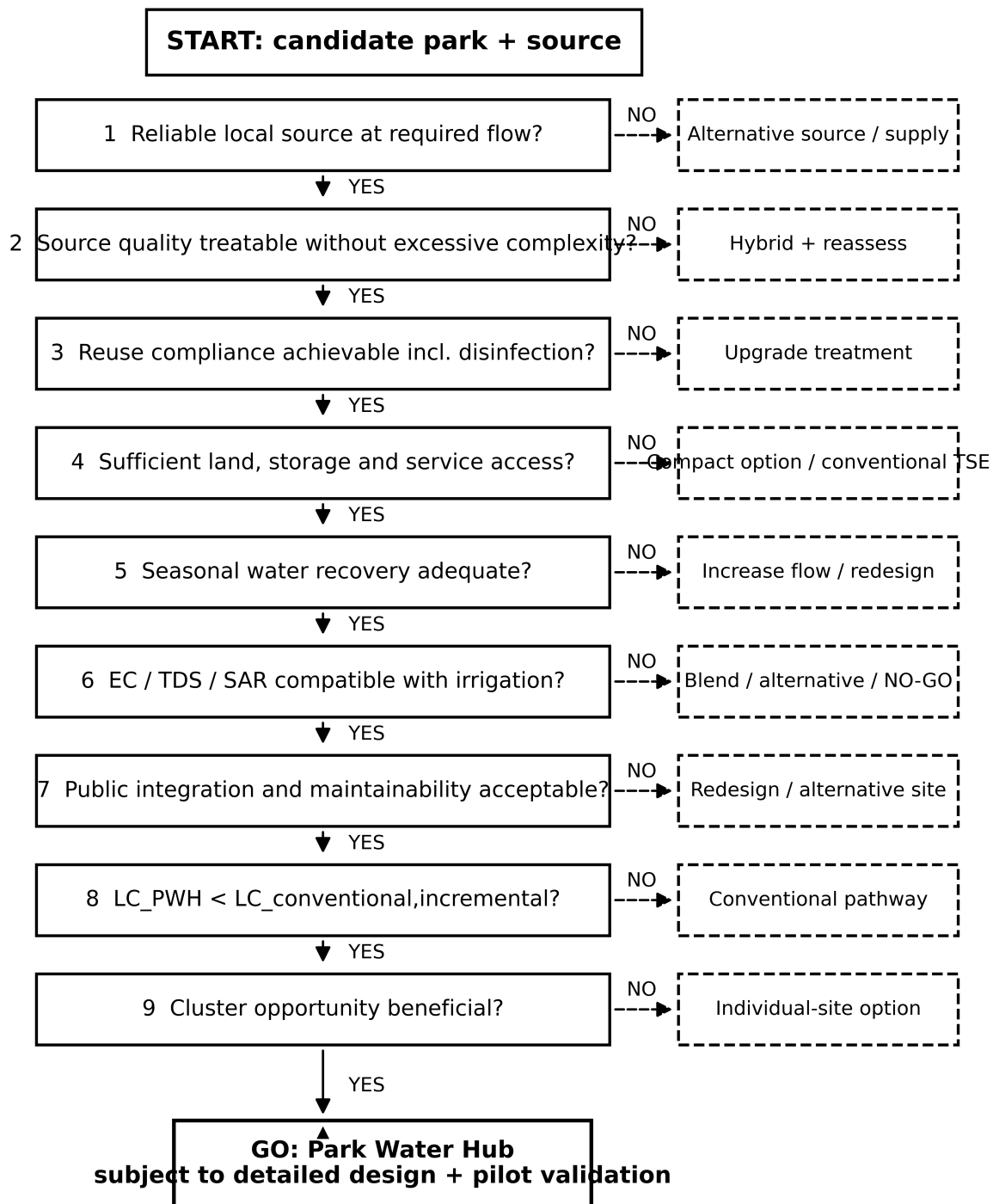


Figure 4

Comparison of analytical source-water cases showing nitrate-denitrification duty, phosphorus-removal duty, aerobic oxygen screening requirement and midpoint delivered-water life-cycle cost



Economic comparison is incremental and site-specific; no universal pipeline-distance threshold is assumed

Figure 5

GO/NO-GO decision sequence for park-integrated VFCWs. Technical and agronomic gates are evaluated before the same-boundary incremental economic comparison

Supplementary Files

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- [04SupplementaryInformation.pdf](#)
- [DiscoverWaterOnlineResource2CalculationWorkbookFINALSUBMIT.xlsx](#)
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