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A CONSTRUCTED WETLAND DESIGNED TO TREAT SECONDARY EFFLUENT: A REVIEW

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ABSTRACT

Conventional secondary treatment reliably reduces biodegradable organic matter and suspended solids, but the effluent it produces still carries residual organics, nutrients, pathogens and trace organic contaminants at concentrations that frequently exceed the limits imposed for discharge into sensitive water bodies or for non-potable reuse. Constructed wetlands (CWs) have emerged as a robust, low-energy tertiary polishing option, particularly for small and medium communities, decentralised campuses and industrial estates where the capital and operating burden of mechanical tertiary units is difficult to sustain. This paper reviews the design basis, removal mechanisms, reported performance and operational constraints of constructed wetlands applied specifically to secondary effluent polishing. Free water surface (FWS), horizontal sub-surface flow (HSSF), vertical sub-surface flow (VSSF) and hybrid configurations are compared with respect to oxygen transfer, footprint, clogging susceptibility and pollutant-specific efficiency. Design methodologies are examined, from empirical areal loading rules to the first-order k–C* and tanks-in-series P–k–C* formulations, together with media selection, vegetation and hydraulic design. Performance data compiled from the literature indicate typical polishing efficiencies of 76–92% for BOD5, 68–86% for COD, 79–91% for TSS, 48–74% for total nitrogen and 42–62% for total phosphorus, with hybrid systems consistently outperforming single-stage beds for nitrogen. Temperature, hydraulic loading rate and hydraulic efficiency are identified as the dominant performance controls, while progressive clogging of the inlet zone remains the principal cause of long-term failure in sub-surface systems. An illustrative design example for a 500 m^3/d secondary effluent stream is presented. The review concludes that constructed wetlands are technically sound and economically attractive polishing units, provided that loading rates are conservative, hydraulic short-circuiting is controlled and phosphorus retention is supported by reactive media.

Keywords: Constructed Wetland; Secondary Effluent; Tertiary Polishing; Nutrient Removal; Hydraulic Loading Rate; K–C* Model; Wastewater Reuse

1 INTRODUCTION

Municipal wastewater treatment plants based on activated sludge, trickling filters, oxidation ditches or sequencing batch reactors are designed principally to stabilise carbonaceous organic matter and to separate settleable solids. The effluent leaving the secondary clarifier of a well-operated plant typically contains 10–30 mg/L of BOD5, 40–100 mg/L of COD and 15–35 mg/L of suspended solids. These values satisfy the general discharge norms of many jurisdictions but fall short of the requirements applied when the receiving water body is nutrient-sensitive, when the effluent is to be reused for irrigation, horticulture, construction, toilet flushing or cooling, or when the discharge point lies upstream of a drinking water intake. Residual nitrogen, phosphorus, faecal indicator organisms and an increasingly scrutinised suite of trace organic contaminants therefore require an additional polishing stage.

Mechanical tertiary options such as rapid sand filtration, cloth-media filtration, membrane filtration, chemical precipitation and ultraviolet or chlorine disinfection are effective but energy-intensive, chemically dependent and demanding of skilled operation. In the Indian context, and more generally across South and South-East Asia, Africa and Latin America, a large proportion of secondary treatment capacity serves populations of fewer than fifty thousand, where continuous power supply, chemical logistics and trained operators cannot be guaranteed. The result is well documented: tertiary units are installed, commissioned and subsequently abandoned.

Constructed wetlands offer an alternative that is deliberately engineered but operationally passive. A constructed wetland is a purpose-built basin, lined to prevent groundwater contamination, filled either with a shallow water column over a soil substrate or with a granular filter medium, and planted with emergent macrophytes. Treatment arises from the same suite of physical, chemical and biological processes that operate in natural wetlands—sedimentation, filtration, sorption, microbial oxidation and reduction, plant uptake and natural die-off—but the processes are constrained within a controlled hydraulic envelope so that performance can be predicted and designed.

1.1 Rationale for reviewing secondary effluent applications specifically

Much of the constructed wetland literature addresses raw or primary-settled sewage, in which the wetland is the principal biological reactor. The polishing application is different in three important respects. First, the influent is already low in particulate organic matter, so oxygen demand within the bed is modest and clogging proceeds more slowly, permitting higher hydraulic loading. Second, nitrogen arrives predominantly as nitrate in nitrifying plants and as ammonium in plants that do not nitrify, and the design must be matched to the prevailing species. Third, the target concentrations are low, so the background or irreducible concentration C* becomes the governing constraint rather than the reaction rate. Design rules transferred uncritically from secondary-treatment wetlands therefore tend to oversize the polishing wetland while still failing to meet nutrient targets.

1.2 Scope and method of the review

This review synthesises design guidance, mechanistic understanding and reported field performance for constructed wetlands receiving secondary effluent. Peer-reviewed journal articles, design manuals and technical guidelines published between 1990 and 2024 were consulted, with emphasis on studies reporting influent and effluent concentrations, loading rates, retention times and system geometry. The values compiled in the tables and plotted in the figures of this paper are representative values assembled from the ranges reported across the consulted literature; they are intended to illustrate trends and to support preliminary design reasoning, and they should be verified against site-specific pilot data before final design. Figure 10 summarises the growth of the literature and the thematic distribution of the studies drawn upon.

2 CHARACTERISTICS OF SECONDARY EFFLUENT AND THE POLISHING REQUIREMENT

The composition of secondary effluent varies with the upstream process configuration, sludge age, temperature and the extent of industrial contribution to the sewerage catchment. Table 1 summarises the ranges commonly encountered and the significance of each parameter for wetland polishing. A long sludge age plant operating above 15 °C will normally nitrify, delivering an effluent low in ammonium but relatively high in nitrate; a high-rate plant will do the opposite. This distinction determines whether the polishing wetland must supply oxygen for nitrification or organic carbon for denitrification, and it is the single most influential piece of information for configuration selection.

Table 1: Typical composition of municipal secondary effluent and its significance for wetland polishing.

Parameter	Unit	Typical range	Design value adopted	Significance for wetland polishing
BOD5	mg/L	10 – 30	20	Low load; supports biofilm but insufficient carbon for full denitrification
COD	mg/L	40 – 100	70	Includes slowly biodegradable and inert fractions; sets residual C*
TSS	mg/L	15 – 35	25	Principal driver of inlet-zone clogging in sub-surface beds
NH4-N	mg/L	1 – 25	8	Requires aerobic zone; high values favour VSSF or hybrid systems
NO3-N	mg/L	2 – 20	12	Requires anoxic zone and carbon source; favours HSSF or FWS
Total nitrogen	mg/L	15 – 35	22	Governs the sizing of the nitrification–denitrification sequence
Total phosphorus	mg/L	3 – 10	6	Retained mainly by sorption; media choice is decisive
pH	–	6.8 – 8.0	7.4	Controls NH3 volatilisation and metal-phosphate precipitation
Alkalinity	mg/L as CaCO3	80 – 250	160	Consumed during nitrification; may limit ammonium oxidation
Dissolved oxygen	mg/L	1.0 – 5.0	2.5	Rapidly depleted within sub-surface media
Faecal coliforms	MPN/100 mL	10^4 – 10^6	10^5	Requires 2–4 log removal for unrestricted reuse
Turbidity	NTU	5 – 20	10	Relevant where downstream disinfection is planned

Table 2 places these values against representative discharge and reuse criteria. The gap between a typical secondary effluent and a reuse-grade water is largest for nitrogen, phosphorus and faecal indicators, and it is precisely these three groups that a properly configured wetland addresses. Organic carbon and suspended solids, by contrast, are usually close to compliance already, so the wetland functions for them as an insurance stage rather than as the primary barrier.

Table 2: Indicative effluent quality targets governing the polishing duty (representative values; the applicable statutory limits must be confirmed for the project location).

Parameter	Unit	Typical secondary effluent	Discharge to inland surface water	Restricted irrigation reuse	Unrestricted / urban reuse
BOD5	mg/L	20	≤ 30	≤ 20	≤ 10
COD	mg/L	70	≤ 250	≤ 100	≤ 50
TSS	mg/L	25	≤ 100	≤ 30	≤ 10
Total nitrogen	mg/L	22	≤ 10 (sensitive)	not restrictive	≤ 10
Total phosphorus	mg/L	6	≤ 2 (sensitive)	not restrictive	≤ 1 – 2
Faecal coliforms	MPN/100 mL	10^5	≤ 1000	≤ 1000	≤ 10 – 100
Turbidity	NTU	10	–	–	≤ 2 – 5

3 CONFIGURATIONS OF CONSTRUCTED WETLANDS

Constructed wetlands are classified first by the position of the water surface and then by the direction of flow. Figure 1 presents idealised cross-sections of the three basic configurations. In a free water surface system the water flows as a shallow open channel across a densely vegetated soil bed; in a horizontal sub-surface flow system the water is kept below the surface of a gravel matrix and flows laterally from inlet to outlet; in a vertical sub-surface flow system the water is dosed intermittently onto the surface of a graded sand bed and percolates downward to an underdrain. Hybrid systems combine two or more stages in series so that alternating aerobic and anoxic conditions can be imposed.

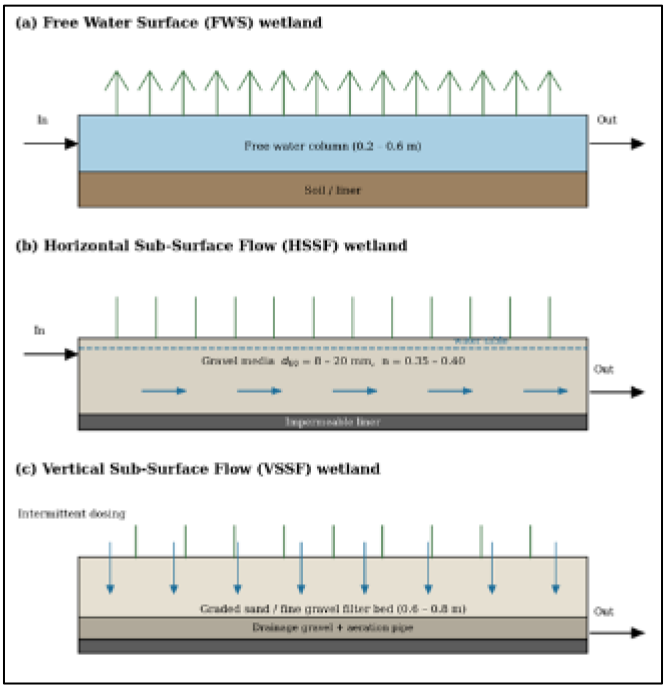

Figure 1: Idealised cross-sections of the principal constructed wetland configurations: (a) free water surface, (b) horizontal sub-surface flow, and (c) vertical sub-surface flow.

The oxygen budget explains most of the performance differences between these configurations. A free water surface bed exchanges oxygen with the atmosphere across the open water surface but consumes much of it in the litter layer. A horizontal sub-surface bed is effectively saturated and largely anoxic, so it nitrifies poorly but denitrifies readily whenever a carbon source is available. A vertical bed is unsaturated between doses; each dose displaces the air in the pore space and draws fresh air in behind it, which is why vertical beds are the strongest nitrifying configuration and the weakest at denitrification. Table 3 compares the configurations across the attributes that matter for a polishing duty.

Table 3: Comparative assessment of constructed wetland configurations for secondary effluent polishing.

Attribute	FWS	HSSF	VSSF	Hybrid (VSSF + HSSF)
Water depth / bed depth	0.2 – 0.6 m water	0.5 – 0.8 m gravel	0.6 – 0.8 m sand + gravel	Stage dependent
Flow regime	Open channel, plug-flow-like	Saturated horizontal	Unsaturated, intermittently dosed	Series operation
Oxygen supply	Moderate (surface + ROL)	Low	High	High then low
Nitrification	Moderate	Poor	Strong	Strong
Denitrification	Moderate	Strong	Weak	Strong
Phosphorus retention	Sedimentation + accretion	Media sorption	Media sorption	Media sorption
Pathogen removal	Good (UV exposure)	Moderate	Moderate	Good

Specific area	3 – 8 m^2/PE	2 – 5 m^2/PE	1 – 3 m^2/PE	3 – 5 m^2/PE
Clogging risk	Low	High at inlet	Moderate (surface)	Moderate
Energy demand	Nil (gravity)	Nil (gravity)	Low (dosing pump)	Low
Mosquito / odour risk	Present	Negligible	Negligible	Negligible
Operational complexity	Low	Low	Moderate	Moderate

4 REMOVAL MECHANISMS

No single process is responsible for treatment in a wetland; removal is the net outcome of many parallel pathways operating at different rates in different zones of the bed. Figure 2 maps these pathways onto the physical structure of a planted bed.

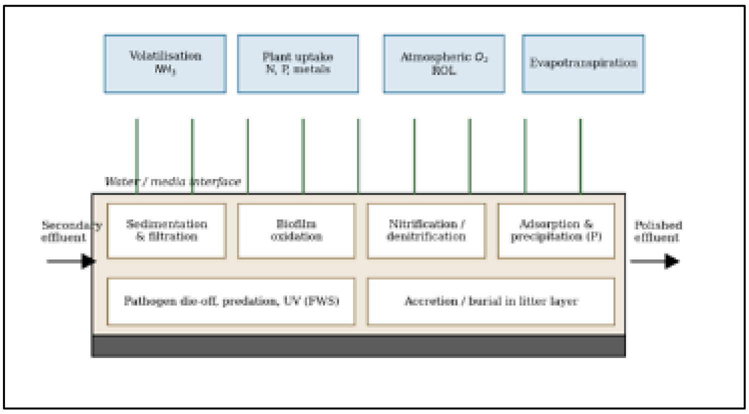

Figure 2: Principal pollutant removal pathways operating within a planted constructed wetland bed.

Suspended solids are removed within the first few metres of the flow path by sedimentation in open-water systems and by straining and interception in granular media. Because this removal is essentially complete and essentially immediate, the solids load is deposited in a very small fraction of the bed volume, which is the physical origin of inlet-zone clogging.

Organic matter is oxidised by heterotrophic biofilm attached to the media, the root surfaces and the litter. In a polishing wetland the readily biodegradable fraction is small, so the measured residual COD is dominated by refractory material that the wetland cannot degrade; this defines the background concentration C^* and explains why COD removal efficiencies reported for polishing wetlands are consistently lower than those reported for wetlands treating primary effluent.

Nitrogen transformation is the most design-sensitive process. Ammonium is adsorbed onto the media and onto organic surfaces, then oxidised to nitrate by autotrophic nitrifiers wherever oxygen is available, principally in the unsaturated zone of a vertical bed and in the rhizosphere microsites created by radial oxygen loss from the roots. Nitrate is subsequently reduced to nitrogen gas by heterotrophic denitrifiers under anoxic conditions in the presence of organic carbon. Since the two steps require opposite redox conditions, a single-stage bed can seldom achieve both, and total nitrogen removal in single-stage systems rarely exceeds about 55%. Anaerobic ammonium oxidation and plant uptake contribute further, although plant uptake is only a permanent removal pathway if the biomass is harvested and exported.

Phosphorus has no gaseous phase. It is retained by ligand exchange and precipitation with calcium, iron and aluminium in the media, by sorption to accreted organic matter and by plant assimilation. Sorption capacity is finite, so phosphorus removal in a wetland built on inert siliceous gravel declines progressively and may approach zero within five to ten years unless reactive media such as calcareous gravel, blast furnace slag, apatite or engineered iron-coated sand are incorporated. Pathogen reduction proceeds through filtration, adsorption, predation by protozoa, natural die-off and, in free water surface systems, ultraviolet exposure; reported reductions of 1–3 log units for faecal coliforms are common, with the higher values associated with longer retention times and open water zones.

Table 4: Dominant removal pathways, rate-controlling factors and preferred configuration by pollutant group.

Pollutant group	Dominant pathways	Rate-controlling factor	Preferred configuration
Suspended solids	Sedimentation, straining, interception	Inlet hydraulics and solids load	Any; FWS if load is variable
Organic matter	Aerobic and anaerobic biofilm oxidation	Oxygen transfer; refractory fraction	VSSF or hybrid
Ammonium	Adsorption, nitrification	Oxygen availability, temperature, alkalinity	VSSF
Nitrate	Denitrification, plant uptake	Available organic carbon, anoxia	HSSF or FWS
Total nitrogen	Sequential nitrification–denitrification	Redox sequencing	Hybrid
Phosphorus	Sorption, precipitation, accretion	Media sorption capacity, contact time	Reactive media bed
Pathogens	Filtration, predation, die-off, UV	Retention time, temperature, sunlight	FWS polishing pond
Trace organics	Sorption, biodegradation, photolysis	Compound hydrophobicity, redox diversity	Hybrid

5 DESIGN CONSIDERATIONS

5.1 Hydraulic design and sizing

The two quantities that determine the size of a wetland are the hydraulic loading rate and the nominal retention time. The hydraulic loading rate is the flow divided by the surface area,

$$HLR = Q / A \qquad (1)$$

and the nominal hydraulic retention time for a sub-surface bed follows from the void volume,

$$HRT = (A \cdot h \cdot n) / Q \qquad (2)$$

where Q is the average daily flow (m^3/d), A the surface area (m^2), h the effective depth (m) and n the porosity of the medium. For a horizontal bed the cross-sectional area must additionally satisfy Darcy's law, so that the bed can convey the design flow without surface breakout:

$$A_c = Q / (k_s \cdot S) \qquad (3)$$

where ks is the saturated hydraulic conductivity of the medium (m/d) and S the applied hydraulic gradient. A conservative practice is to design the cross-section using a fraction, commonly one tenth, of the clean-medium conductivity, so that the bed retains hydraulic capacity as clogging develops. The aspect ratio of a horizontal bed should generally lie between 2:1 and 4:1; very long narrow beds improve plug flow but demand excessive head, while wide short beds are prone to short-circuiting.

5.2 Kinetic design models

Areal loading rules are convenient but transfer poorly between climates. The first-order areal model with a background concentration is the most widely used rational basis:

$$(C_e - C^*) / (C_i - C^*) = \exp(-k_A / q) \qquad (4)$$

in which Ci and Ce are influent and effluent concentrations, C* the irreducible background concentration, kA the areal rate constant (m/yr) and q the hydraulic loading rate expressed in the same units. Because real wetlands are not ideal plug-flow reactors, the tanks-in-series form, known as the P–k–C* model, is preferred:

$$(C_e - C^*) / (C_i - C^*) = [\, 1 + k_A / (P \cdot q) \,]^{-P} \qquad (5)$$

where P is the apparent number of tanks in series, obtained from tracer testing and typically between 3 and 6 for a well-constructed bed. Rate constants are temperature-dependent and are corrected using the modified Arrhenius relationship:

$$k_T = k_{20} \cdot \theta^{(T-20)} \quad (6)$$

Figure 7 illustrates both effects. Panel (a) shows how strongly nitrogen removal responds to temperature relative to phosphorus, which is largely a physico-chemical process; panel (b) shows that increasing hydraulic efficiency from a single well-mixed tank to five tanks in series raises predicted removal by roughly ten percentage points at the same loading, which is achieved at no capital cost simply by improving inlet and outlet distribution.

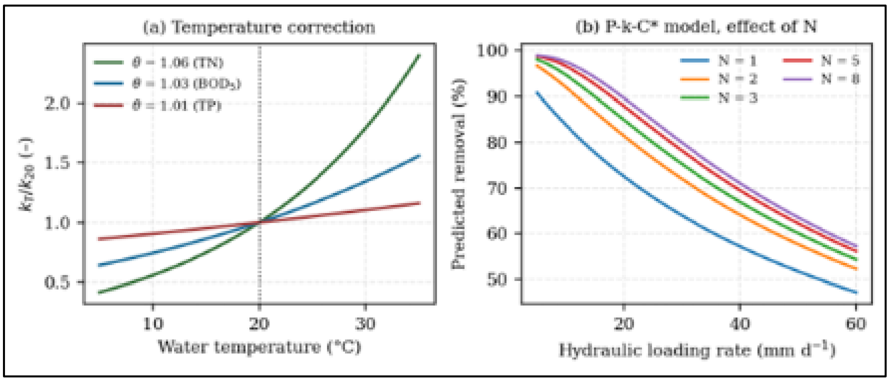

Figure 7: (a) Temperature correction factors for typical θ values; (b) sensitivity of predicted removal to the number of tanks in series in the P–k–C* model.

5.3 Media selection

Media must simultaneously provide hydraulic conductivity, biofilm surface area and phosphorus sorption capacity, and these requirements conflict. Fine media offer surface area and sorption but clog; coarse media convey flow but treat poorly. The common resolution is a graded profile: coarse cobbles in the inlet and outlet distribution zones, a working medium in the body of the bed and, where phosphorus is critical, a reactive polishing layer near the outlet. Table 5 compares media in current use.

Table 5: Comparison of filter media used in sub-surface flow constructed wetlands.

Medium	Grain size (mm)	Porosity (–)	Conductivity ks (m/d)	P sorption (mg/kg)	Remarks
Washed siliceous gravel	8 – 16	0.35 – 0.40	1000 – 5000	20 – 100	Standard HSSF medium; negligible long-term P retention
Coarse sand	1 – 4	0.30 – 0.38	100 – 500	50 – 200	Standard VSSF medium; surface clogging must be managed
Crushed limestone	5 – 12	0.38 – 0.45	800 – 3000	250 – 800	Ca-driven P precipitation; raises pH and alkalinity
Blast furnace slag	5 – 20	0.40 – 0.50	500 – 2500	1000 – 4000	High P capacity; leaches alkalinity and metals initially
Light expanded clay (LECA)	4 – 10	0.40 – 0.55	600 – 2000	300 – 900	Light, high surface area; higher unit cost
Zeolite (clinoptilolite)	2 – 8	0.40 – 0.48	300 – 1200	100 – 300	High ammonium exchange capacity; buffers shock loads
Iron-coated / ferric sand	1 – 5	0.30 – 0.36	80 – 400	1500 – 5000	Engineered P sink; regeneration is impractical

5.4 Vegetation

Emergent macrophytes contribute in four ways: they supply attachment surface below ground, they transfer oxygen to the rhizosphere through aerenchyma, they assimilate nutrients into biomass, and they insulate the bed surface in winter while stabilising it against erosion. Direct nutrient uptake accounts for only a modest share of removal in a loaded wetland—commonly 5–15% of the nitrogen and phosphorus load—and it is reversible unless the aboveground biomass is cut and removed at the end of the growing season. Species selection should favour locally native, non-invasive plants adapted to the prevailing climate and to the salinity and nutrient status of the effluent. Table 6 summarises species widely used in tropical and subtropical installations.

Table 6: Macrophyte species commonly employed in constructed wetlands and their functional attributes.

Species	**Common name**	**Rooting depth (m)**	**Radial O2 loss**	**N uptake ($g/m^2 \cdot yr$)**	**Remarks**
Phragmites australis	Common reed	0.6 – 1.0	High	200 – 500	Most widely used; vigorous, can be invasive
Typha latifolia / angustifolia	Cattail	0.3 – 0.5	Moderate	150 – 450	Tolerant of high loads; shallow rooting
Canna indica	Indian shot	0.3 – 0.6	Moderate	100 – 300	Ornamental; well suited to campus systems
Cyperus papyrus / alternifolius	Papyrus / umbrella sedge	0.4 – 0.7	Moderate	180 – 400	High biomass yield in tropical climates
Colocasia esculenta	Taro	0.2 – 0.4	Low	80 – 250	Fast establishment; harvestable biomass
Heliconia psittacorum	Parrot flower	0.3 – 0.5	Moderate	90 – 260	Ornamental; suited to landscape integration

5.5 Recommended design criteria

Table 7 consolidates the design criteria that recur across the guidance documents and field studies consulted for this review, expressed for the polishing duty rather than for secondary treatment. The values are deliberately conservative; where pilot data are available, site-specific rate constants should replace them.

Table 7: Recommended design criteria for constructed wetlands polishing secondary effluent.

Design parameter	**Unit**	**FWS**	**HSSF**	**VSSF**
Hydraulic loading rate	cm/d	1.5 – 5.0	3.0 – 8.0	6.0 – 20.0
Nominal HRT	d	3 – 7	2 – 5	0.5 – 2
Areal BOD5 loading	$g/m^2 \cdot d$	2 – 6	4 – 8	8 – 20
Areal TN loading	$g/m^2 \cdot d$	1 – 3	2 – 5	3 – 8
Water / bed depth	m	0.2 – 0.4	0.5 – 0.7	0.6 – 0.8
Aspect ratio (L : W)	–	3:1 – 10:1	2:1 – 4:1	1:1 – 2:1
Bed slope (base)	%	0.5 – 1.0	0.5 – 1.0	1.0 (drainage)
Media porosity	–	n.a. (soil)	0.35 – 0.40	0.30 – 0.38
Design conductivity fraction	–	n.a.	0.10 of clean ks	n.a.
Dosing frequency	cycles/d	continuous	continuous	4 – 12
Freeboard	m	0.3	0.15 – 0.25	0.15 – 0.25
Planting density	$shoots/m^2$	4 – 6	4 – 8	4 – 8

6 REPORTED PERFORMANCE OF POLISHING WETLANDS

Figure 3 summarises the mean removal efficiencies compiled across the configurations, with the bars indicating the spread reported between studies. The pattern is consistent and mechanistically explicable. Removal of organics and solids is high and relatively insensitive to configuration, because these processes are physical and fast. Ammonium removal separates sharply, with vertical and hybrid beds achieving close to 90% and horizontal beds barely half that. Total nitrogen removal is highest in hybrid systems, where the two redox environments are provided in sequence. Phosphorus removal is the weakest and the most variable outcome for every configuration, reflecting the finite and site-specific sorption capacity of the media.

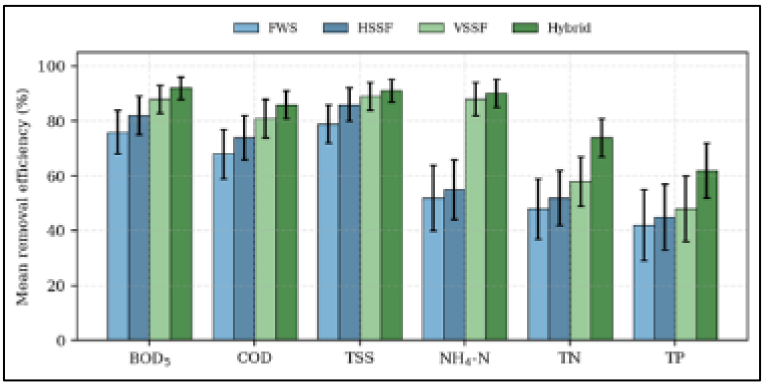

Figure 3: Mean removal efficiencies by wetland configuration for the principal pollutant groups; error bars indicate the range reported across the studies compiled.

Figure 4 expresses the same behaviour as a function of retention time using the first-order model. The curves rise steeply up to approximately three days and then flatten as the concentration approaches the background value. Beyond about five days the additional land requirement buys very little further improvement, which is why the commonly adopted design window lies between three and five days for horizontal systems. Phosphorus is the exception: its curve is flat throughout, confirming that phosphorus removal is limited by sorption capacity rather than by contact time, and that extending the retention time is not a remedy for poor phosphorus performance.

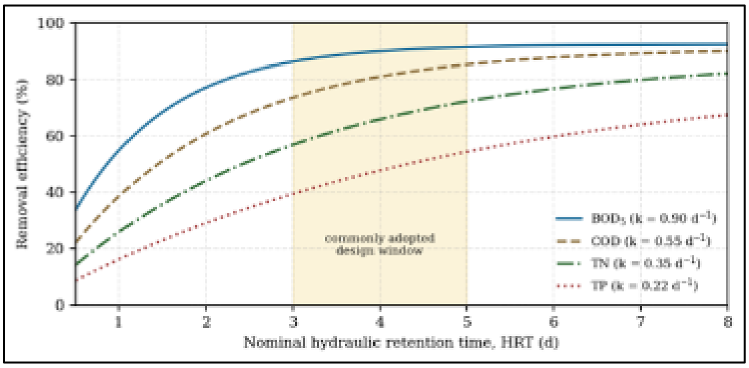

Figure 4: Predicted removal efficiency as a function of nominal hydraulic retention time using the first-order k–C* model with representative rate constants.

The relationship between areal loading and performance, shown in Figure 5, contains the central design trade-off. Percentage removal declines monotonically as loading increases, but the mass removed per unit area continues to rise. A wetland designed purely to maximise areal mass removal would therefore be loaded heavily and would produce poor effluent; a wetland designed for the highest percentage removal would be uneconomically large. The practical compromise for horizontal sub-surface beds treating secondary effluent lies near an areal BOD5 load of 6–8 $g/m^2 \cdot d$, beyond which the accumulation rate of solids and biofilm in the inlet zone begins to outpace the rate at which it can be mineralised, and clogging becomes progressive rather than steady-state.

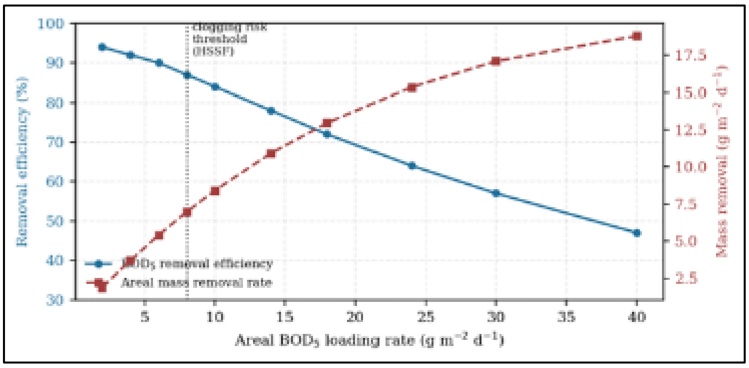

Figure 5: Removal efficiency and areal mass removal rate as functions of areal BOD5 loading, showing the loading beyond which clogging becomes progressive in HSSF beds.

Seasonal behaviour is shown in Figure 6. Organic matter removal varies only modestly through the year because the physical mechanisms are temperature-insensitive and the biological ones retain adequate capacity even in cool weather. Nitrogen removal, in contrast, varies by more than twenty percentage points between the coolest and warmest months, following water temperature closely; nitrification is the limiting step and its rate constant carries a high temperature coefficient. Phosphorus is almost flat, again consistent with a sorption-controlled mechanism. For design in temperate or high-altitude locations, the implication is that the wetland must be sized on the cold-season rate constant if year-round nitrogen compliance is required, which may increase the area by fifty to eighty percent relative to a design based on annual mean temperature.

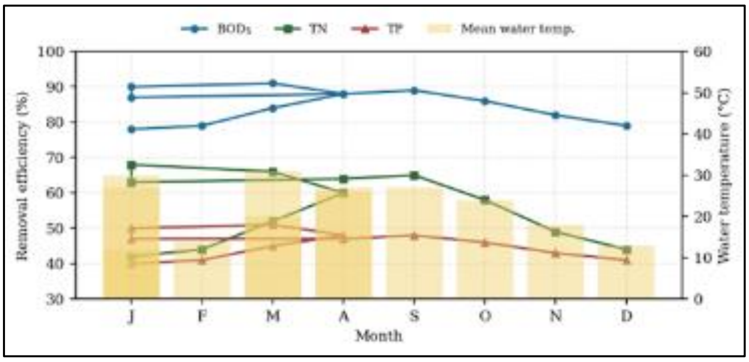

Figure 6: Seasonal variation in removal efficiency for BOD5, total nitrogen and total phosphorus with mean water temperature superimposed.

Table 8 compiles representative outcomes reported for polishing wetlands across a range of configurations, scales and climates. Two observations follow from it. First, hydraulic loading rate is a better predictor of performance than retention time alone, because it embeds both flow and geometry. Second, systems reporting the highest nitrogen removal are, without exception, either hybrid or operated with effluent recirculation, confirming that redox sequencing rather than residence time is the determining factor.

Table 8: Representative performance of constructed wetlands polishing secondary effluent, compiled from the reviewed literature

System / scale	Configuration	Climate	HLR (cm/d)	HRT (d)	BOD5 (%)	TSS (%)	TN (%)	TP (%)
Municipal, 2000 m^3/d	FWS	Warm temperate	2.4	6.0	74	80	46	38
Municipal, 500 m^3/d	HSSF	Subtropical	5.0	3.5	84	88	50	44
Campus, 120 m^3/d	HSSF	Tropical	6.5	2.8	81	85	48	41
Municipal, 300 m^3/d	VSSF	Subtropical	12.0	1.2	89	90	56	47

Pilot, 20 m^3/d	VSSF	Semi-arid	15.0	0.9	90	91	52	43
Municipal, 800 m^3/d	Hybrid VSSF+HSSF	Temperate	8.0	4.0	93	92	72	58
Municipal, 150 m^3/d	Hybrid with recirculation	Subtropical	9.5	3.2	94	93	78	61
Industrial estate, 400 m^3/d	HSSF, slag media	Tropical	5.5	3.0	82	86	51	76
Polishing pond + FWS	Pond–FWS series	Tropical	3.0	7.5	78	83	55	40
Aerated HSSF, 250 m^3/d	Intensified HSSF	Temperate	14.0	1.5	95	92	68	49

Faecal indicator reduction across the same set of studies ranged from approximately 1.2 to 3.4 log units, with free water surface stages and longer retention times occupying the upper end of that band. Reported removals of trace organic contaminants were considerably more variable: readily biodegradable and sorbing compounds were attenuated by 70–95%, whereas persistent and polar compounds frequently passed through with attenuation below 40%. Hybrid systems, which present a wider range of redox conditions, consistently outperformed single-stage beds for this class of contaminant.

7 ILLUSTRATIVE DESIGN EXAMPLE

To demonstrate the application of the criteria assembled above, a hybrid polishing wetland is sized for a secondary effluent flow of 500 m^3/d with the influent quality adopted in Table 1 and a target of BOD5 ≤ 10 mg/L, TN ≤ 10 mg/L and TP ≤ 2 mg/L for unrestricted non-potable reuse. A vertical stage is placed first to nitrify the residual ammonium, followed by a horizontal stage in which the nitrate produced is denitrified, with 50% recirculation of the horizontal-stage effluent to the head of the vertical stage to supply nitrate to the anoxic zone and to dilute the incoming load. Table 9 sets out the calculation.

Table 9: Worked sizing calculation for a hybrid polishing wetland treating 500 m^3/d of secondary effluent.

Step	Quantity	Basis / expression	Value	Remarks
1	Design flow, Q	Average dry weather flow	500 m^3/d	Peak factor 1.5 checked on hydraulics
2	Recirculation ratio, R	Selected	0.50	Total flow through VSSF = 750 m^3/d
3	VSSF hydraulic loading	Table 7, adopted	10 cm/d	Conservative for sand medium
4	VSSF area	A = Q(1+R)/HLR	7500 m^2	Two beds of 3750 m^2 for alternation
5	VSSF depth and porosity	Adopted	0.75 m; n = 0.34	Graded sand over drainage gravel
6	VSSF nominal HRT	Eq. (2)	≈ 0.26 d	Intermittent dosing, 8 cycles/d
7	HSSF hydraulic loading	Table 7, adopted	5 cm/d	Within clogging-safe range
8	HSSF area	A = Q(1+R)/HLR	15 000 m^2	Two cells, aspect ratio 3:1
9	HSSF depth and porosity	Adopted	0.60 m; n = 0.38	Washed gravel, 8–16 mm
10	HSSF nominal HRT	Eq. (2)	≈ 4.6 d	Within the 3–5 d design window

11	Darcy check	Eq. (3), ks = 0.1 × 2000 m/d, S = 0.01	Required cross-section 3.75 m^2; provided 42 m^2	Ample hydraulic reserve
12	Areal BOD5 load	Q·C/A (HSSF)	0.67 $g/m^2 \cdot d$	Well below the 6–8 $g/m^2 \cdot d$ threshold
13	Predicted BOD5 out	Eq. (5), kA = 33 m/yr, P = 4, C* = 3	≈ 4 mg/L	Meets the 10 mg/L target
14	Predicted TN out	Eq. (5), kA = 14 m/yr, P = 4, C* = 3.5	≈ 7 mg/L	Meets the 10 mg/L target
15	Predicted TP out	Eq. (5), kA = 10 m/yr, P = 4, C* = 1.2	≈ 2.6 mg/L	Reactive media layer required
16	Total wetland footprint	Steps 4 and 8 plus 15% for bunds and access	≈ 2.6 ha	≈ 5.2 m^2 per m^3/d treated

The calculation illustrates the two characteristic outcomes of polishing wetland design. Organic matter and nitrogen targets are met comfortably once the redox sequence is provided, whereas phosphorus falls short and requires a deliberate intervention—here a reactive sorptive layer of calcareous gravel or slag in the outlet zone of the horizontal stage, sized on its measured sorption capacity and replaceable at intervals. The footprint of roughly 5 m^2 per m^3/d of treated flow is the price of the passive operation, and it is the constraint that most often decides whether a wetland is feasible at a given site.

8 OPERATIONAL CHALLENGES AND LONG-TERM BEHAVIOUR

Clogging is the dominant long-term failure mode of sub-surface systems. Figure 9(a) shows the characteristic pattern: hydraulic conductivity falls rapidly in the inlet zone where the solids and biofilm accumulate, while the outlet zone remains close to its original condition for many years. The consequence is not uniform loss of capacity but a progressive migration of the effective inlet downstream, accompanied by surface breakout at the head of the bed and a shortening of the effective flow path.

Hydraulic efficiency deteriorates in parallel. Figure 9(b) shows residence time distributions for different numbers of tanks in series; a bed that behaves as three or four tanks when new can degrade towards single-tank behaviour as preferential channels form, which alone can reduce removal by ten to fifteen percentage points without any change in loading or biology. Tracer testing at commissioning and at intervals thereafter is therefore a far more informative diagnostic than effluent sampling alone.

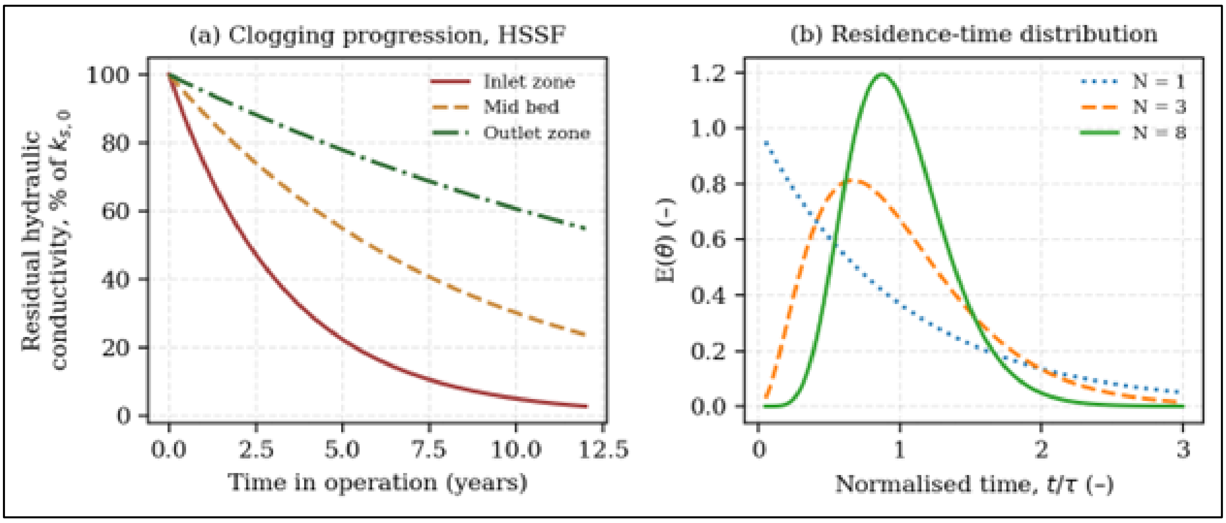

Figure 7: (a) Progressive decline in hydraulic conductivity by zone in an HSSF bed; (b) residence time distributions for different tanks-in-series numbers.

Table 10: Common operational problems, their causes and mitigation measures.

Problem	Cause	Symptom	Mitigation
Inlet clogging	Solids and biofilm accumulation	Surface ponding near inlet, short-circuiting	Effective pre-treatment; distributed inlet manifold; replaceable coarse inlet zone; resting cycles
Short-circuiting	Poor inlet/outlet distribution, uneven settlement	Low tracer P value, reduced removal	Level spreaders, baffles, periodic re-grading; verify by tracer test
Poor nitrification	Oxygen limitation, low temperature, low alkalinity	High effluent ammonium	Add VSSF stage; intermittent dosing; artificial aeration; alkalinity dosing
Poor denitrification	Carbon limitation	High effluent nitrate	Recirculation; internal carbon from plant litter; supplemental carbon dosing
Declining P removal	Exhaustion of media sorption sites	Effluent TP approaching influent TP	Reactive media layer with planned replacement; chemical dosing where critical
Weed invasion / plant loss	Water level mismanagement, salinity, pests	Bare patches, reduced ROL	Water level control, replanting, seasonal harvesting
Mosquito breeding (FWS)	Stagnant open water	Public health complaints	Depth variation, larvivorous fish, deep-zone circulation
Odour	Anaerobic surface conditions	Nuisance at inlet	Reduce load, sub-surface inlet, resting cycles

Routine operation is otherwise limited: inlet and outlet inspection, water level adjustment, removal of accumulated screenings, annual harvesting of aboveground biomass where nutrient export is intended, and periodic desludging of the preceding settling unit. It is the discipline of the pre-treatment stage, more than any feature of the wetland itself, that determines whether the design service life of fifteen to twenty-five years is achieved.

9 COMPARISON WITH ALTERNATIVE TERTIARY OPTIONS

Figure 8 places wetlands alongside conventional polishing technologies on the two axes that decide selection in practice: land requirement and operating cost. Sand filtration occupies almost no land but carries a high operating burden of backwashing, power and skilled attention. Wetlands invert that relationship. The choice is therefore rarely technical: where land is available at reasonable cost and operator capability is limited, the wetland is the stronger option; where land is scarce and operations are professionalised, it is not. A secondary consideration, increasingly significant, is that wetlands deliver ecological and amenity co-benefits—habitat, microclimate moderation, landscape value and carbon sequestration in the accreting litter layer—that mechanical units do not.

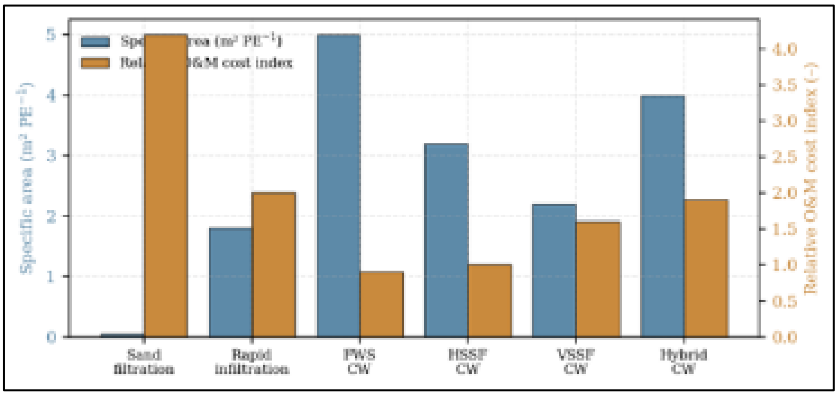

Figure 8 Specific land requirement and relative operation and maintenance cost index for tertiary polishing alternatives.

10 RESEARCH TRENDS, GAPS AND FUTURE DIRECTIONS

Figure 10 shows the sustained growth of the constructed wetland literature and the thematic distribution of the studies drawn upon in this review. Nutrient removal remains the largest theme, but the fastest-growing areas are emerging contaminants and intensified designs. Despite this volume of work, several gaps recur.

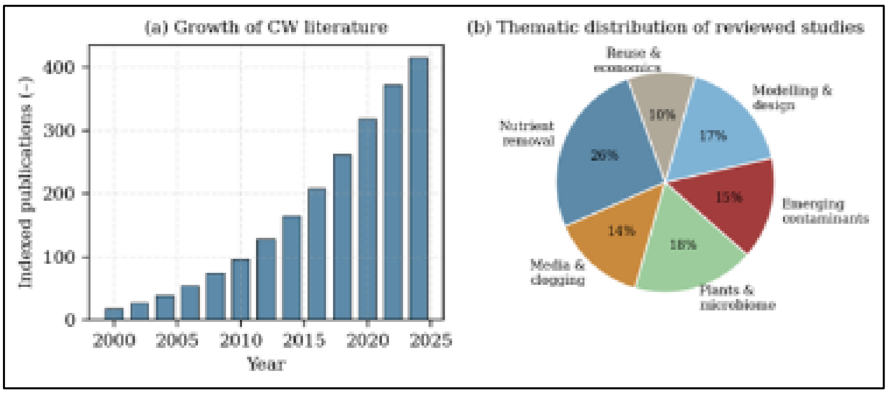

Figure 9: (a) Growth of indexed constructed wetland publications; (b) thematic distribution of the studies compiled for this review.

Table 11: Identified research gaps and suggested directions.

Gap	Present limitation	Suggested direction
Long-term phosphorus retention	Most reported data cover one to three years, before sorption sites are exhausted	Decade-scale monitoring; standardised media sorption testing; designed replaceable P layers
Cold-climate nitrogen removal	Rate constants derived from warm-season data are applied year-round	Winter-specific kinetics; insulation, thermal storage and aerated designs
Clogging prediction	Empirical and site-specific; no accepted predictive model	Coupled hydraulic–biofilm models validated by long-term conductivity mapping
Emerging contaminants	Removal is inconsistent and mechanisms are poorly separated	Redox-resolved batch studies; transformation product identification
Greenhouse gas balance	Nitrous oxide and methane fluxes seldom reported alongside treatment data	Standardised flux monitoring integrated into performance studies
Design standardisation	Wide variation in reported loading definitions hinders comparison	Common reporting protocol for HLR, HRT, area basis and sampling regime
Reuse-oriented operation	Design targets discharge norms rather than reuse quality	Coupling with disinfection; risk-based reuse guidance for wetland effluent

11 CONCLUSION

Constructed wetlands are a technically sound and operationally forgiving means of polishing secondary effluent, and the evidence reviewed here supports several specific conclusions.

Removal of organic matter and suspended solids from secondary effluent is reliable across all configurations, with typical efficiencies of 76–92% for BOD5 and 79–91% for TSS; these parameters seldom govern design.

Nitrogen removal is governed by redox sequencing rather than by retention time. Single-stage beds rarely exceed 55% total nitrogen removal, whereas hybrid arrangements with recirculation consistently reach 70–78%.

Phosphorus is the limiting parameter. Removal is sorption-controlled, declines with media age and cannot be improved by enlarging the wetland; reactive media with planned replacement are required wherever a phosphorus limit applies.

Hydraulic efficiency deserves the same design attention as reaction kinetics. Improving the apparent tanks-in-series number from one to four raises predicted removal by roughly ten percentage points at zero additional area, and it is achieved through inlet and outlet distribution detailing alone.

Areal loading for horizontal sub-surface beds treating secondary effluent should remain below approximately 6–8 g BOD5/m^2·d; above this, inlet clogging becomes progressive rather than steady-state and service life is curtailed.

Temperature sensitivity is concentrated in the nitrogen pathway. Where year-round nitrogen compliance is required in cool climates, sizing on the cold-season rate constant may increase the area by fifty to eighty percent.

The typical footprint of a hybrid polishing wetland is of the order of 5 m^2 per m^3/d of treated flow. Land availability, not treatment capability, is the usual constraint on adoption.

For small and medium installations in warm climates—the circumstances of most of South Asia—the constructed wetland remains among the few tertiary technologies whose performance can be expected to survive a decade of ordinary institutional operation. Its wider adoption depends less on further optimisation of removal efficiency than on conservative loading, disciplined pre-treatment, deliberate provision for phosphorus and the standardisation of design and reporting practice.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare no competing financial or personal interests.

Data availability

Data supporting the findings are available from the corresponding author on reasonable request.

Author contributions

Conceptualisation and supervision, Author One; construction, operation and monitoring, Author Two; data analysis and manuscript preparation, Author Three. All authors approved the final manuscript.

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