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Decentralised Wetland Polishing for Pollutant Load Reduction in River-Dependent Water Supply System

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Abstract: Urban water security in Malaysia is closely linked to river systems that function simultaneously as effluent receivers and raw water sources. In river-dependent supply configurations in which treated effluent is discharged upstream of potable abstraction points, concentration-based compliance does not fully represent the cumulative pollutant mass transported downstream. This study evaluates the mass-based pollutant interception performance of a pilot-scale mobile constructed wetland (MCW) system treating a portion of the effluent from a sewage treatment plant (STP) in Selangor, Malaysia. Using measured post-STP and post-MCW treatment concentrations, pollutant loads were quantified in kg/day and annualised under steady-state assumptions. The MCW achieved measurable reductions in total suspended solids (50%), biochemical oxygen demand (62.6%) and ammoniacal nitrogen (90.5%), translating into daily mass interception before river transport. Proportional scaling scenarios indicate that expanded polishing capacity could yield substantial cumulative load reductions upstream of the abstraction reach. Given that the STP discharge occurs upstream of the potable intake, upstream mass interception reduces the cumulative pollutant burden conveyed towards downstream treatment facilities. The findings highlight the analytical distinction between concentration compliance and mass-based management and demonstrate how decentralised polishing can function as an incremental buffering mechanism that enhances resilience within river-dependent urban water systems.

Keywords: Integrated Water Resource Management, Mobile Constructed Wetland (MCW), Pollutant Load Assessment, Pollutant Removal, Total Maximum Daily Load (TMDL), Urban Water Security

1. Introduction

Urban water security in Malaysia is closely linked to the condition of its river systems, which remain the primary raw water source for municipal supply [1]. In rapidly developing catchments, sewage treatment plants (STPs) discharge treated effluent into river tributaries that may be located upstream of potable abstraction points, creating hydrological linkages between wastewater discharge and downstream supply.

In Malaysia, wastewater discharge is regulated primarily through concentration-based standards that ensure effluent quality meets prescribed limits at the point of release [2]. These regulations by the Department of Environment are structured around concentration-based standards (mg/L), ensuring that effluent quality meets environmental thresholds before release. This regulatory framework is effective in safeguarding receiving waters from acute local impacts and maintaining compliance with environmental quality objectives.

Recent compliance monitoring data of STPs indicate that all STPs achieve consistently high adherence rates across regulated parameters (Table 1 – source [2]). Average compliance exceeds 90% for key indicators, including biochemical oxygen demand (BOD) (93%), chemical oxygen demand (COD) (94%), suspended solids (SS) (93%) and ammoniacal nitrogen (NH_3–N) (92.5%). These figures reflect strong regulatory performance at the point of discharge.

Table 1 STP Compliance Level (2019).

Effluent Quality	Parameters' Compliance Level (%)				
	BOD	COD	SS	Ammonia	O&G
Standard A	92	96	95	92	97
Standard B	94	92	91	93	92
Average	**93**	**94**	**93**	**92.5**	**94.5**

While such compliance demonstrates effective implementation of concentration-based standards, point-source adherence does not explicitly represent cumulative pollutant mass transported downstream within river-dependent systems. In catchments where treated effluent is discharged upstream of potable abstraction points, aggregate loading from multiple compliant facilities may still influence basin-scale water quality dynamics.

Recent river monitoring data [3], as illustrated in Figure 1, indicate that while the proportion of clean rivers increased from 61% in 2019 to 71% in 2024, approximately one-third of

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monitored rivers remain classified as slightly polluted and polluted. Although these trends reflect overall improvement, the persistence of slightly polluted and polluted rivers suggests continued cumulative pressures from upstream discharges and diffuse inputs**.** In river-dependent supply systems, such cumulative mass inputs may influence river assimilative capacity and increase treatment requirements at downstream water treatment plants (WTPs). For example, upstream pollution events have previously led to unscheduled water supply disruptions in Selangor, affecting over one million consumers, highlighting the sensitivity of abstraction points to upstream water quality conditions [4].

A further structural consideration relates to the operational profile of Malaysia's STPs. Of the approximately 7000 STPs that are currently in operation nationwide [5], a substantial proportion continue to comply with Standard B discharge requirements, which permit higher concentration limits for parameters, such as BOD and NH_3–N, compared to Standard A facilities [6]. While both standards meet regulatory compliance, the cumulative mass discharged from numerous Standard B facilities may contribute to sustained loading within river basins. Upgrading all existing STPs to stricter standards presents considerable financial and operational challenges, reinforcing the importance of complementary load-based management strategies at the basin scale.

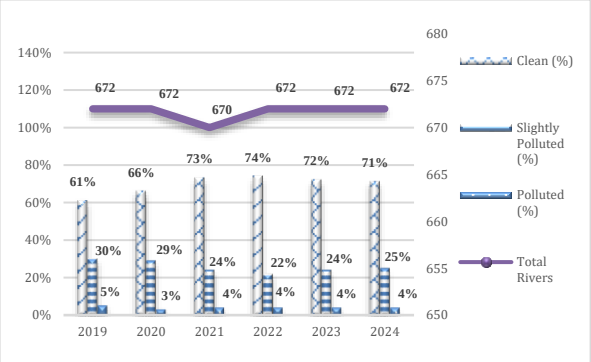

Figure 1: Trend in River Water Quality Classification (2019–2024).

In this context, load-oriented management approaches provide an analytical framework for evaluating cumulative pollutant inputs beyond concentration compliance. Total maximum daily load (TMDL) frameworks, for example, quantify the maximum pollutant mass that a water body can assimilate while maintaining designated water quality standards [7]. Rather than focusing solely on concentration limits at individual discharge points, TMDL approaches quantify allowable pollutant mass (e.g., kg/day) and allocate this total load among point sources, non-point sources and background contributions within the basin.

Empirical evidence from multiple watersheds indicates that TMDL implementation has led to measurable reductions in nutrient concentrations and improvements in water quality indicators, such as BOD and total phosphorus [8], [9]. For example, long-term monitoring in the Chesapeake Bay watershed shows progress towards nutrient reduction goals, with point source controls largely implemented and non-point source management advancing [10]. Action plans were also developed from TMDL calculations and have facilitated targeted pollution control measures, including infrastructure investments and best management practices [7], [11].

In upstream–downstream configurations where treated effluent is discharged before potable abstraction, such as in the Sungai Langat basin, river systems function as transport corridors linking discharge points to intake zones. Following discharge, pollutants are conveyed downstream through a defined river tributary before entering the abstraction zone. Although dilution and in-stream processes may alter concentrations along this pathway, the total mass introduced at the discharge point remains a fundamental determinant of the pollutant load arriving at the intake reach. This load-based perspective aligns with river basin–scale water resource management, which has been widely recognised as the appropriate unit for integrated management in highly urbanised and jurisdictionally fragmented systems[12].

Within this context, decentralised polishing mechanisms in STPs may offer incremental but measurable reductions in pollutant mass before river transport, thereby contributing to basin resilience without necessitating full-scale infrastructure replacement or upgrading.

Mobile Constructed Wetlands (MCW) represent a modular nature-based polishing approach designed to be integrated downstream of existing STPs [6], [7]. While previous studies have examined their treatment efficiency and water security contributions, limited research has quantified their role in intercepting pollutant mass loads before river discharge or explored their implications for basin-scale water security.

This paper evaluates the pollutant load reduction performance of a pilot-scale MCW system treating a portion of STP effluent in Selangor. By calculating mass interception at pilot scale and modelling potential scaling scenarios, the study examines the role of decentralised wetland polishing as a complementary strategy within river-based urban water systems.

2. Methodology

The study was conducted at a STP - HLT219 Bandar Bukit Mahkota, located within the Langat River Basin, Selangor, Malaysia. The STP discharges an average of 8,797 m^3/day of treated effluent into a river reach situated approximately 7 km upstream (river distance) of the raw water abstraction point, supplying the Semenyih 2 WTP.

Given this upstream-downstream configuration, treated effluent from the STP contributes to the pollutant mass entering the abstraction reach after in-stream transport and dilution. Although discharge complies with regulatory concentration standards, cumulative mass loading remains relevant to source-water quality and downstream treatment requirements.

A pilot-scale MCW system was installed to polish approximately 9 m^3/day of diverted effluent before discharge, enabling evaluation of decentralised pollutant load interception upstream of a potable water intake. Figure 2 shows the schematic illustration of the pilot-scale Mobile Constructed Wetland (MCW) system. The MCW system consists of a modular tank measuring approximately 7 m × 2 m × 2 m (L × W × D), divided into four compartments.

The treatment configuration includes:

- A free-floating wetland compartment planted with *Eichhornia crassipes*
- Two vertical sub-surface flow compartments planted with *Thalia geniculata* and *Chrysopogon zizanioides*
- A final substrate-only polishing compartment

Effluent is introduced into the first compartment using a solar-powered pump. Flow proceeds sequentially through the compartments, allowing physical filtration, sedimentation,

microbial degradation and plant-assisted nutrient uptake processes to occur. The average hydraulic loading rate corresponds to a treatment capacity of 9 m³/day, representing approximately 0.1% of total STP discharge.

The pilot-scale MCW system utilised in this study has been previously described in detail [13], where concentration-based removal efficiency and water security implications were assessed. In contrast, the current study adopts a mass-based analytical framework to evaluate pollutant load reduction and source-water protection relevance.

Water samples were collected at two monitoring points:

- Post-STP discharge (pre-MCW treatment)
- Post-MCW effluent (before return to discharge stream)

The following parameters were analysed by an accredited laboratory using standard methods: TSS, BOD_5, COD, NH_3–N and pH.

Pollutant load (kg/day) was calculated using Eq. (1).

$$L = \frac{(C*Q)}{1000} \quad (1)$$

where:
L = pollutant load (kg/day)
C = concentration (mg/L)
Q = flow rate (m³/day)

Pollutant loads were calculated using the treated MCW flow (9 m³/day) to estimate pilot-scale interception. To evaluate potential basin-scale implications, proportional scaling scenarios were modelled using the total average STP discharge (8,797 m³/day), assuming comparable removal efficiencies. Annual load reduction was estimated by multiplying daily load interception by 365 days under steady-state operation assumptions. This modelling exercise does not represent current operational performance but illustrates potential cumulative impact under expanded implementation.

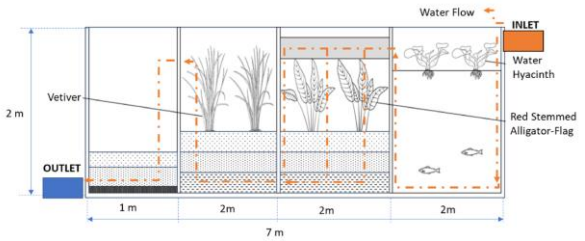

Figure 2: Schematic illustration of the pilot-scale Mobile Constructed Wetland (MCW) system.

3. Results

3.1. Concentration Reduction

TSS decreased from 4.00 to 2.00 mg/L, while BOD_5 declined from 5.05 to 1.89 mg/L. NH_3–N reduced from 0.21 to 0.02 mg/L. COD showed a moderate decrease from 15.4 to 14.3 mg/L.

Although baseline effluent concentrations were already within regulatory compliance limits, the MCW provided additional polishing before discharge. Among the parameters monitored, NH_3–N exhibited the highest relative reduction, indicating effective removal within the polishing system.

Table 2 summarises pollutant concentrations measured at post-STP and post-MCW monitoring points. The pilot-scale MCW system demonstrated measurable reductions in selected pollutant concentrations between post-STP and post-MCW treatment conditions. TSS decreased from 4.00 to 2.00 mg/L, while BOD_5 declined from 5.05 to 1.89 mg/L. NH_3–N reduced from 0.21 to 0.02 mg/L. COD showed a moderate decrease from 15.4 to 14.3 mg/L.

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Table 2 Post-STP and Post-MCW Concentrations.

Parameters	Post-STP (mg/L)	Post-MCW (mg/L)	% Reduction
TSS	91	2.00	97.8%
BOD	26	3.5	86.54%
COD	95.4±4.2	11.0	88.47%
NH_3–N	1.34	0.01	99.25%

The observed reductions indicate that the MCW provided additional polishing beyond regulatory compliance levels. NH_3–N exhibited the highest relative reduction, suggesting effective nitrification or plant uptake within the polishing compartments. Although COD reduction was comparatively modest, the overall trend reflects incremental improvement before discharge.

3.2. Load Interception by MCW

Using the load equation presented in Section 2 and an average treated flow of 9 m³/day, pollutant load reductions were calculated on a mass basis. Furthermore, annual load reductions were subsequently estimated by assuming steady-state operation throughout the year (365 days). The results of these calculations are presented in Table 3.

Table 3 Load Interception by MCW.

Parameters	Daily Load Interception (kg/day)	Annual Load Interception (kg/year)
TSS	0.801	292.4
BOD	0.203	74.1
COD	0.760	277.4
NH_3–N	0.012	4.4

The mass-based calculation demonstrates that even low concentration differences translate into measurable daily pollutant mass interception when expressed in kg/day. This distinction is particularly relevant in river systems where cumulative loading influences downstream abstraction conditions.

3.3. Contribution Relative to Total STP Discharge & Scaling Scenario

In Selangor, public STPs collectively generate approximately 3,435 million litres per day (MLD) of treated effluent [14], indicating substantial potential for pollution load interception at the basin scale. At the facility level, the pilot-scale MCW currently treats approximately 0.1% of the STP discharge (9 m³/day out of 8,797 m³/day).

To explore broader implementation potential, a conservative interception scenario representing 0.1% of total treated effluent statewide (3.435 MLD) was modelled. Under this scenario, projected annual pollutant load reduction is estimated at approximately 3.96 tonnes of BOD and 2.51 tonnes of TSS. While for COD and NH_3–N, they are 1.38

tonnes and 0.24 tonnes, respectively. Although modest relative to total discharge volumes, these values demonstrate measurable upstream mass interception achievable through incremental deployment.

It is important to note that the annual load projections presented here assume steady-state operation; however, actual mass interception in a real-world implementation would be subject to seasonal variability and hydraulic fluctuations. The study area in central Selangor experiences a humid tropical climate with high annual rainfall (1,900–2,600 mm), which contributes to substantial stormwater generation and influences hydrological loading.

Observations during the research noted that lab-scale trials occurred during a relatively wetter period, while pilot-scale monitoring was conducted during a hotter season. These differing climatic conditions can influence system behaviour, specifically water temperature, evapotranspiration rates and biological treatment kinetics. Furthermore, intense rainfall events may lead to wet-weather dilution of the STP effluent, altering influent quality and hydraulic retention characteristics.

While the steady-state model provides a useful estimate of potential impact, these seasonal and hydraulic variables introduce uncertainties that could cause actual annual interception to deviate from projected estimates. Future evaluations should incorporate long-term monitoring across multiple monsoon cycles to refine the reliability of these annualised mass-reduction figures.

These projections are also illustrative and assume consistent removal performance and steady-state operation across expanded treatment capacity. It is imperative to acknowledge the operational limitations and uncertainties associated with extrapolating pilot-scale performance to basin-scale implementation. The current pilot-scale MCW evaluation focused primarily on short-to-medium-term operational performance. Scaling up assumes consistent removal efficiency; yet, full-scale, long-term operations may be susceptible to media ageing effects, such as substrate clogging, compaction, nutrient saturation and gradual reductions in filtration and adsorption capacity, which could influence overall treatment efficiency over time.

Furthermore, uncertainties remain regarding how continuous influent variability that arises from fluctuations in daily sewage loading, wet-weather dilution, and upstream treatment performance would impact a basin-scale system over an extended period. Consequently, while the scaling scenario highlights the significant potential of decentralised polishing for mass load reduction, future long-term monitoring will be necessary to fully assess performance robustness under variable climatic, hydraulic and loading conditions. While not representative of current operational conditions, the modelling exercise provides an estimate of cumulative load interception potential at full-scale polishing.

The study STP discharges into a river reach located approximately 7 km upstream of the potable abstraction point. Along this transport corridor, in-stream processes, such as dilution, sedimentation and biogeochemical transformation, may modify pollutant concentrations; however, the total mass introduced at the discharge point remains a primary determinant of the load conveyed towards the intake zone.

Accordingly, upstream mass interception reduces the cumulative pollutant burden entering the abstraction reach. The mass-based results therefore quantify the incremental buffering effect introduced within the upstream–downstream system configuration, linking plant-scale interception to downstream source-water conditions.

4. Discussion

4.1. Implication for Upstream Abstraction

The results demonstrate that additional polishing can yield measurable reductions in pollutant mass even when baseline effluent concentrations comply with regulatory standards. This distinction underscores the analytical difference between concentration-based compliance and mass-based loading assessment. While discharge standards ensure environmental thresholds are met at the point of release, river systems integrate cumulative mass inputs across space and time.

In upstream–downstream configurations where treated effluent enters the river before potable abstraction, the abstraction point effectively receives the aggregate influence of upstream discharges. Under such conditions, concentration compliance alone does not fully represent the cumulative pollutant burden conveyed to intake zones. A mass-based perspective, therefore, provides a complementary lens for evaluating upstream contributions within river-dependent supply systems.

4.2. Relevance of Ammoniacal Nitrogen to Downstream Treatment Operations

Among the monitored parameters, NH_3–N exhibited the highest relative reduction at the pilot scale. Although baseline concentrations were within regulatory limits, even low levels of NH_3–N in raw water can influence downstream treatment processes. In conventional potable water treatment systems, NH_3–N interacts with chlorination practices, potentially increasing chlorine demand and affecting disinfection efficiency. Variability in upstream NH_3–N loading may therefore contribute to operational adjustments at abstraction-based treatment plants.

Given that the STP discharge occurs approximately 7 km upstream of the potable intake, upstream reductions in NH_3–N translate into reduced nitrogen mass conveyed towards the abstraction reach. While in-stream nitrification and dilution processes may attenuate concentrations along the transport corridor, mass interception at the source reduces the total load requiring transformation before abstraction. In this respect, decentralised upstream polishing may provide incremental operational buffering for downstream treatment systems.

4.3. Incremental Resilience Mechanism

The findings suggest that decentralised polishing mechanisms can function as incremental buffering layers within river-dependent supply systems. Rather than replacing centralised treatment infrastructure, such systems provide distributed interception upstream of abstraction points, reducing cumulative mass before river transport. This layered configuration introduces an additional barrier within the upstream–downstream pathway.

From a systems perspective, resilience in water supply networks is strengthened when risk is distributed rather than concentrated at a single treatment stage [15], [16]. In configurations where potable abstraction relies on upstream water quality conditions, mass interception at the wastewater stage reduces the burden placed on downstream treatment processes. Although the pilot-scale interception represents a small proportion of total discharge, proportional scaling illustrates how expanded implementation could enhance redundancy and buffering capacity within the basin.

In this context, decentralised polishing contributes not only to effluent quality improvement but also to system-level robustness, particularly under conditions of fluctuating river flow or episodic pollution events.

4.4. Comparative Performance Benchmarking

The pollutant removal efficiencies observed in the pilot-scale MCW are highly competitive when compared with international constructed wetland and decentralised polishing studies. The system's performance in removing TSS (97.8%) and BOD (86.54%) aligns with high-efficiency benchmarks reported for vertical flow systems in temperate climates, such as those in Germany [17], which achieved TSS and BOD reductions exceeding 93% and 90%, respectively.

In the context of tropical climates, the MCW demonstrated superior organic matter removal compared to similar decentralised wetlands. For instance, studies in Ethiopia [18] reported more modest COD removal rates of 62%–65%. The pilot-scale MCW's 88.47% COD removal significantly exceeds these figures, likely due to the optimised substrate depth and multi-compartment design. Furthermore, the near-complete removal of Ammoniacal Nitrogen (99.25%) matches peak performance levels reported in horizontal subsurface flow systems in Egypt [19] (99.3%), underscoring the effectiveness of the MCW's rhizosphere-mediated nitrification processes. These comparisons validate the MCW as a high-performance polishing solution capable of delivering effluent quality that meets or exceeds global standards for decentralised wastewater reclamation.

4.5. Implications for Basin-Scale Management and Policy Alignment

The load-based findings presented in this study reinforce the importance of evaluating cumulative pollutant mass within river-dependent supply systems. While concentration compliance remains a necessary regulatory safeguard, basin-scale water security requires consideration of aggregate loading conveyed to abstraction zones. Analytical frameworks that emphasise pollutant mass allocation, such as load-based management approaches, provide a complementary perspective for linking plant-scale discharge to catchment-scale outcomes.

A conservative modelling scenario representing interception of 0.1% of total treated effluent statewide (3.435 MLD) demonstrates that even limited deployment could yield measurable annual reductions of approximately 3.96 tonnes of BOD and 2.51 tonnes of TSS before river transport. While modest relative to total discharge volumes, such reductions illustrate the cumulative significance of incremental upstream mass interception when evaluated across the basin scale. These findings reinforce the practical relevance of load-based assessment in identifying distributed opportunities for pollution mitigation within river-dependent systems.

Within the Malaysian context, the Water Sector Transformation 2040 (AIR2040) agenda emphasise integrated water resource management, system efficiency and long-term resilience. The concept of upstream mass interception through decentralised polishing aligns with these objectives by introducing distributed buffering within existing infrastructure networks. Rather than relying solely on downstream treatment optimisation, incremental load reduction at source contributes to system robustness across the upstream–downstream continuum.

Although the present study is based on pilot-scale implementation, the modelling results illustrate how expanded polishing capacity could enhance cumulative load management at the basin scale. Such an approach supports preventive source-water protection strategies and complements ongoing efforts towards sustainable and resilient water sector transformation.

5. Conclusion

This study examined pollutant load interception by a pilot-scale MCW system treating STP effluent discharged upstream of a potable abstraction point within a river-dependent supply system. While baseline effluent concentrations complied with regulatory standards, mass-based analysis demonstrated measurable reductions in daily and annual pollutant loading before river transport. These findings highlight the analytical distinction between concentration compliance and cumulative mass management in upstream–downstream configurations.

The results further indicate that decentralised polishing can function as an incremental buffering mechanism, particularly for parameters such as NH_3–N that influence downstream treatment operations. Although the current pilot-scale MCW treats only a small fraction of total discharge, proportional scaling illustrates the potential magnitude of cumulative load reduction achievable under expanded implementation.

From a basin-scale perspective, upstream mass interception complements existing regulatory frameworks and aligns with integrated water resources management objectives. By introducing distributed treatment barriers within the wastewater-to-abstraction pathway, decentralised polishing contributes to system resilience in river-dependent urban water networks. Future work may explore multi-site deployment and flow-variability scenarios to further evaluate cumulative basin-level impact.

Declaration of Competing Interest

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

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