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Article

Strategic Engineering Framework for Water Quality Resilience: Synergizing Passive Tidal Flushing with Active Ecological Interventions in Urban Canals

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Abstract

Urban micro-tidal canals frequently suffer from severe hypoxia due to restricted hydrodynamic exchange and untreated discharges. Field monitoring during a 2022 mass fish mortality event at the Dongsam tidal canal revealed that during the ‘tidal window gap’—a hydraulic stagnation period required for passive tidal flushing—bottom-layer dissolved oxygen plummeted to a critical anoxic state (0.44 mg/L). To overcome passive tidal exchange limitations, this study proposes a hybrid water purification framework integrating active ecological interventions: wall-mounted spiral flow aeration for continuous oxygenation and vertical bio-curtains for pollutant interception. Synergizing fluid mechanics with ecological engineering, core design parameters were systematically derived: effective mixing width ($W_{eff} \approx 2.5h$), longitudinal spacing ($L_s = 10 \times W_{eff}$), optimal root immersion ratio ($D_r/h = 0.6$), and climate-adaptive planting densities ($\rho_p \approx 12\text{--}32$ plants/m²). Additionally, a corrosion-resistant FRP guide rail system was incorporated to facilitate autonomous adaptation to tidal fluctuations. The framework was conceptualized through a prototype design for the Dongsam canal and subsequently scaled to 15 international micro-tidal canals across diverse climatic zones. Ultimately, this research presents a comprehensive methodological framework and a flexible engineering toolkit intended to guide future water quality and ecological resilience enhancements in shallow urban waterways worldwide.

Keywords: urban tidal canals; dissolved oxygen (DO); spiral flow aeration; vertical bio-curtain; floating treatment wetlands (FTWs); tidal window gap; ecological resilience

1. Introduction

The rapid coastal urbanization of recent decades has led to the construction of numerous artificial canal systems, characterized by complex geometric structures and restricted water circulation. In shallow urban waterways such as the Dongsam tidal canal (hereinafter referred to as the canal), which exhibits a micro-tidal range and shallow bathymetry, natural tidal flushing alone is often insufficient to maintain ecological health. The limited hydraulic gradient in these systems leads to chronic stagnation, significantly increasing water residence times [1]. Combined with artificial nutrient loads from urban outfalls, this results in a significant degradation of water quality.

Traditionally, high-energy mechanical pumping has been used to address these issues, but the energy-water-carbon nexus demands a shift toward sustainable, low-carbon alternatives that minimize operational costs and environmental impacts.

To improve energy efficiency, prior research has explored the possibility of harnessing natural tidal energy. Gravity-driven seawater exchange systems have been shown to utilize tidal potential energy to enhance water quality in restricted coastal environments [2]. In shallow waters with minimal natural convection, the strategic operation of tidal gates is crucial for inducing artificial hydraulic gradients and promoting water exchange.

Jin et al. [3] demonstrated that bi-directional tidal gate operation utilizing the tidal range significantly increases the physical flow velocity within the Dongsam tidal canal. Hong et al. [4] confirmed through long-term field observations that this enhanced hydraulic circulation leads to tangible improvements in overall water quality indicators. However, such hydraulic improvements alone cannot guarantee long-term ecological stability.

A critical vulnerability remains in the form of oxygen-depletion windows during tidal phase transitions, known as the 'Tidal window gap.' This phenomenon stems from the mandatory closure of the gates while awaiting a sufficient tidal head difference (ΔH_{max}) to drive the flushing process. During this stagnation, the absence of flow results in the cessation of physical transport processes, ultimately leading to a rapid depletion of dissolved oxygen (DO) due to accumulated organic loading.

In this study, through in-situ monitoring and empirical analysis of the canal during the 2022 large-scale fish mortality event, we quantitatively characterize this inter-tidal stagnation as the primary driver of ecological collapse in such passive systems. Despite the operational seawater exchange system, acute nutrient surges during these stagnant intervals caused DO levels to fall significantly below critical survival thresholds. This incident underscores the urgent need for complementary management systems that mitigate hypoxia without relying solely on energy-intensive mechanical solutions.

This study therefore proposes a hybrid methodological framework to overcome the operational limitations of existing passive systems. This framework integrates two key components: a wall-mounted spiral flow aerator to provide an active oxygen supply during stagnation periods, and a vertical bio-curtain designed to physically intercept and mitigate point-source nutrient inflows directly at the outfalls. The study's significance lies in its scalability and efficiency. The system is designed to maximize the utilization of natural tidal potential energy, thereby minimizing external power requirements. It also provides a standardized adaptation matrix that enables the flexible scaling of hybrid components based on canal geometry (width W and water depth h), ambient temperature, and physicochemical characteristics such as salinity and pollutant load intensity.

While the physical implementation and empirical validation of the proposed hybrid system remain subjects for future field-scale studies, this research provides a rigorously structured, theoretically grounded methodology evaluated across 15 international canals. In compliance with ASCE/EWRI and EPA standards [5,6], this study presents a proactive, resilience-based approach to coastal infrastructure management, shifting the focus from reactive post-treatment to strategic disaster prevention in shallow urban tidal canals worldwide.

2. Materials and Methods

2.1. Study area

The Dongsam tidal canal (Busan, South Korea) is selected as the representative study site to demonstrate the proposed hybrid methodological framework for low-velocity urban waterways. As illustrated in Figure 1, the central portion of the canal is geographically positioned at approximately 35° 04' 29.6" N and 129° 04' 30.9" E. Its location is presented at two hierarchical scales: a broader regional perspective of Yeongdo-gu, Busan (a), and a detailed local layout of the canal (b).

This artificial waterway has a total length of 2.1 km, comprising a 1.6 km open channel section and a 0.5 km covered culvert. The canal features a trapezoidal cross-section with a representative

width of 10 m and a varying shallow bathymetry, with water depths fluctuating between 0.9 m and 2.1 m depending on the tidal phase. Specifically, the coastal area of Busan is classified as a micro-tidal environment. According to the annual tidal observation data and tide tables provided by the Korea Hydrographic and Oceanographic Agency (KHOA) [7], Busan Port exhibits a micro-tidal range, with a mean of approximately 1.2 m and a maximum tidal range (ΔH_{max}) of roughly 1.5 m, which is insufficient for maintaining adequate natural seawater exchange. During the stagnant 'Tidal Window Gap', when gates are closed to build hydraulic head for subsequent flushing, the canal retains a highwater level. Consequently, an operational water depth of approximately 2.0 m is established as the baseline (based on the 2022 daily gate operation logs provided by the Yeongdo-gu office) for evaluating hypoxia mechanisms and designing the aeration system in the following sections.

To enhance this limited hydrodynamic circulation, recent studies have investigated the operation of bi-directional sluice gates installed at the northern and southern ends of the canal. Previous hydrodynamic modeling and field observations demonstrated that maximizing tidal range drainage through these gates significantly increases the internal flow velocity [3]. Furthermore, it has been demonstrated that this bidirectional water circulation enhances baseline levels of common water quality indicators, such as dissolved oxygen (DO) and chemical oxygen demand (COD), under normal conditions [4]. However, while these passive operational strategies mitigate chronic pollution, they remain fundamentally insufficient to prevent the acute formation of anoxic layers during the critical stagnant phases of the tidal cycle, thereby necessitating the active hybrid framework proposed in this study.

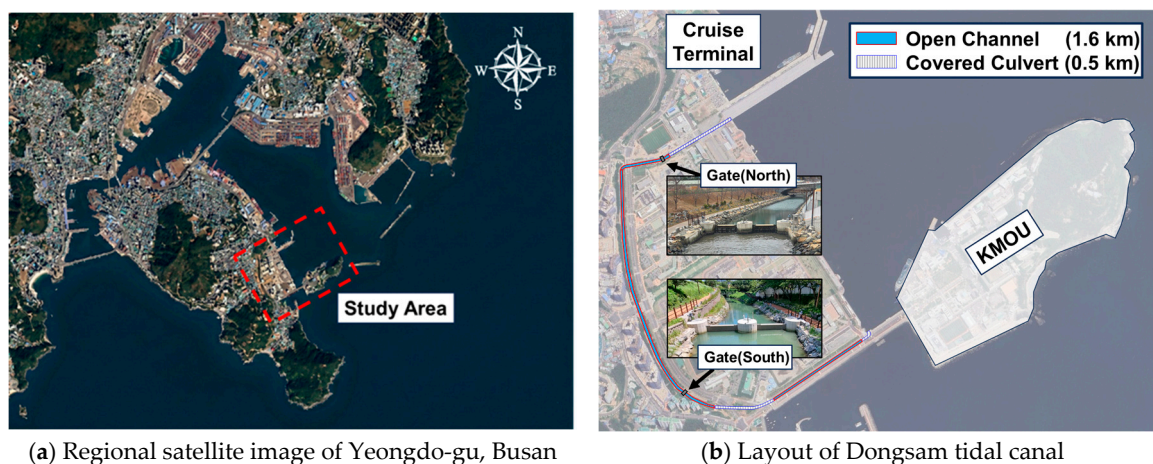


Figure 1. Location and configuration of the study area.

2.2. Monitoring Network and Data Acquisition

2.2.1. Monitoring Network: Internal, Discharge, and Downstream Stations

To systematically analyze the spatial distribution of water quality and evaluate the effectiveness of the hybrid framework, a multi-layered monitoring network was established across the 2.1 km waterway. As illustrated in Figure 2, the monitoring network is designed to capture the spatial variability of water quality across the entire canal system, consisting of three distinct categories of monitoring locations:

- **Bridge-based Monitoring Stations (B-series):** These stations are situated at strategic locations throughout the 1.6 km open channel section, selected based on the necessity for representative water quality assessment and ease of monitoring accessibility. Each station in the B-series is positioned at a bridge crossing, allowing for reliable access to the center-line of the canal's width. This configuration ensures that the collected data accurately reflect the integrated water quality status while facilitating consistent long-term monitoring. These stations serve as the primary

baseline for evaluating the canal's general environmental conditions prior to the implementation of the proposed hybrid system.

- **Urban Discharge Points (D-series):** The urban discharge points (D-series) are defined as urban sewage outfalls where artificial effluent enters the tidal stream intermittently, often driven by irregular urban drainage or rainfall events. These locations are anticipated to exhibit high concentrations of COD, TN, and TP, reflecting the significant organic and nutrient loading typical of such episodic urban runoff. Consequently, these points are considered optimal candidates for the installation of vertical bio-curtains, which are designed to intercept nutrient and organic plumes at the source. The deployment of these components at the D-series points is intended to block the influx of pollutants before they disperse into the internal canal body, thereby mitigating hypoxia risks during stagnant tidal phases (Tidal Window Gaps).
- **Downstream Terminal Stations (KMOU-series)** Positioned near the southern tidal gate near Korea maritime & ocean university, the KMOU-series stations serve as critical boundary reference points representing both ambient seawater conditions and downstream impacts. By monitoring the quality of the effluent as it discharges toward the open sea and comparing it with incoming tidal water, these stations provide a boundary reference to assess the net environmental impact of the canal on the broader coastal ecosystem. This allows for a clear distinction between internally generated pollutant loads and the background water quality of the Busan coastal area.

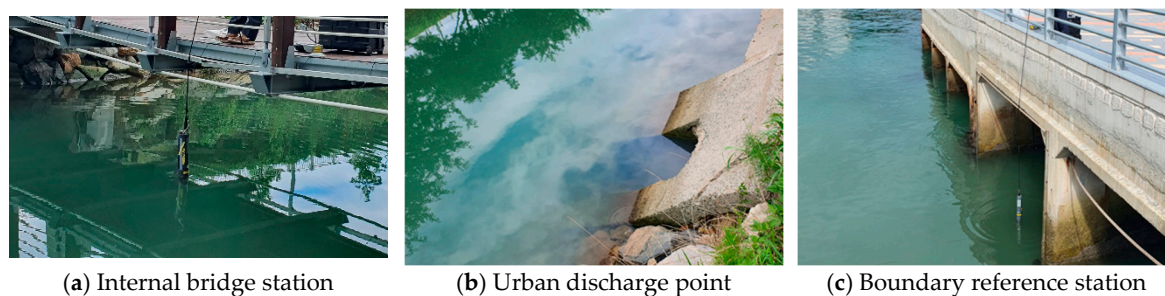


Figure 2. Functional classification of the water quality monitoring network.

The spatial distribution of the classified monitoring stations— comprising the internal (B-series) stations, discharge (D-series) points, and boundary reference (KMOU-series) stations—is delineated in Figure 3.

2.2.2. Instrumentation and Analytical Protocol

The monitoring framework was established to characterize on-site water quality conditions in real-time and to identify specific pollution-inducing factors. As shown in Figure 4, in-situ measurements were taken using a YSI 650 MDS multiparameter meter to record real-time changes in water quality parameters, primarily focusing on dissolved oxygen (DO) dynamics. Figure 4a specifically provides visual documentation of the monitoring process carried out at station B-6. Figure 4b shows the resulting empirical output, displaying the raw DO data recorded at the surface layer of station B-6 on 1st August 2022. The direct correlation between the physical field deployment and the subsequent raw data output visually validates the reliability and precision of the longitudinal field measurements discussed in Section 3. To account for potential vertical variability, measurements were systematically performed at both the surface and bottom layers of each station. This vertical profiling was essential to identify the degree of vertical stratification and to detect localized hypoxic conditions that often develop in the deeper layers during stagnant tidal phases. This approach allowed for the immediate identification of environmental stress within the canal under various tidal regimes.

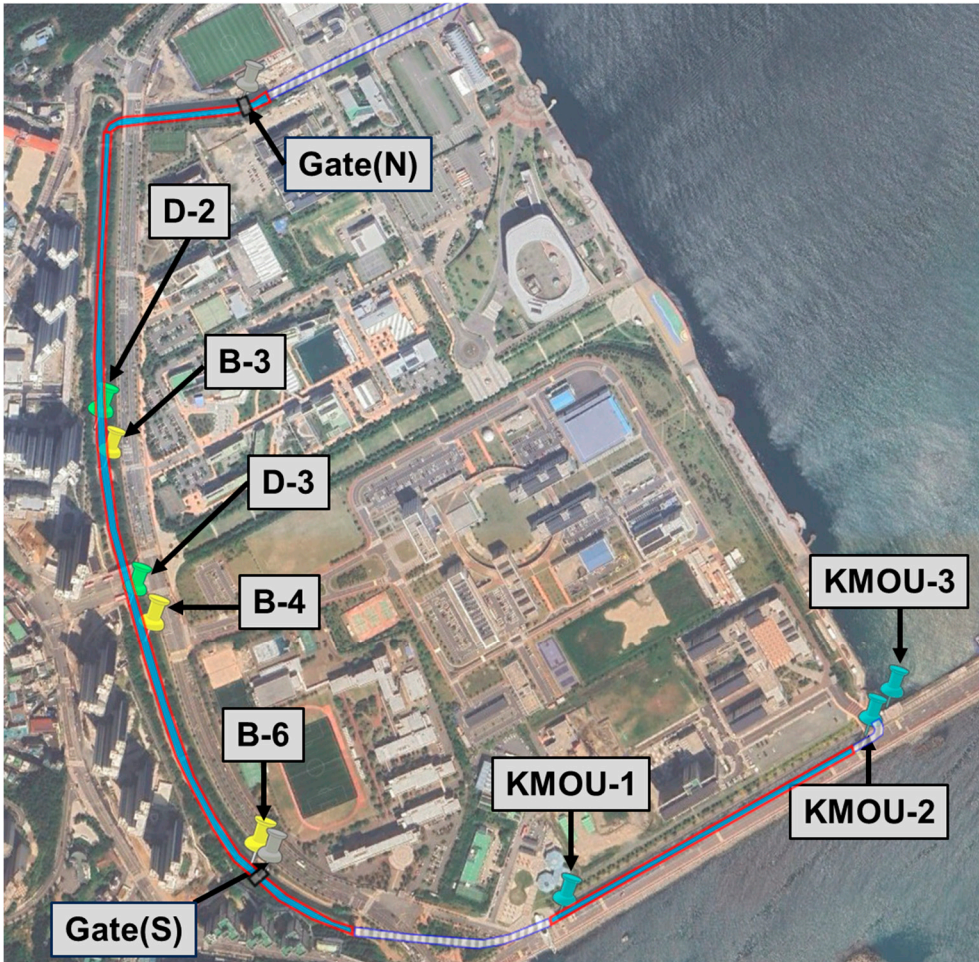
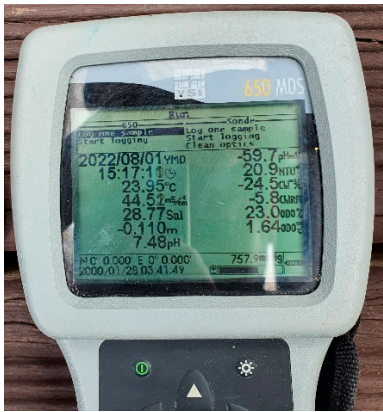


Figure 3. Spatial distribution of the monitoring network within the canal.



(a) Deployment of the multiparameter sonde



(b) Raw data displayed on the YSI 650 MDS

Figure 4. In-situ water quality monitoring and data validation.

To complement these field observations, manual seawater samples were collected from the S, B, and D-series monitoring points for rigorous laboratory analysis (Figure 5a). These samples were used to quantify key anthropogenic pollutants, specifically chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP) (Figure 5b,c). To ensure data integrity, all collected samples were preserved at 4°C and transported to the laboratory for analysis within 24 hours.

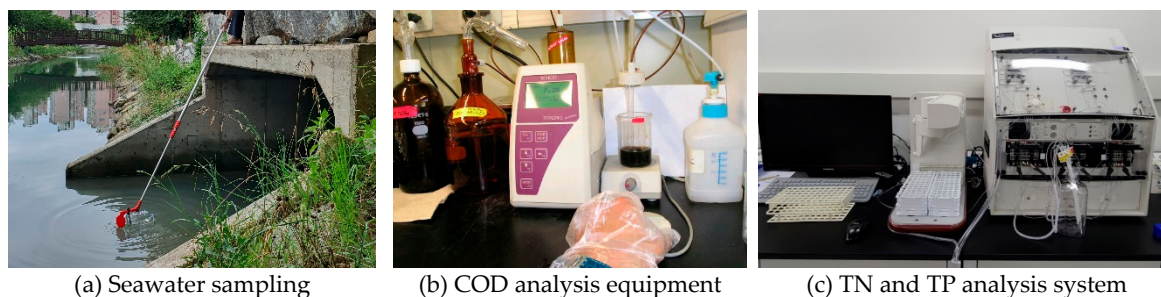


Figure 5. Field sampling and laboratory analytical equipment for water quality assessment.

2.3. Passive Hydraulic Exchange Mechanism and Tidal Window Gap

The water circulation within the canal is primarily driven by a passive dual-gate tidal exchange system, designed to maximize the utilization of natural tidal potential energy. Given the shallow bathymetry ($h \approx 2\text{m}$) and limited natural hydraulic gradient of the canal, the strategic operation of these gates is an indispensable necessity to induce the artificial hydraulic head difference (ΔH) required for effective flushing.

The hydraulic behavior during gate operation can be fundamentally described by the relationship between the potential energy gradient and the resulting velocity (v).

Based on the classical principles of energy conservation and orifice flow dynamics in open channels [8,9], the flow velocity induced by the hydraulic head difference when the gates are opened can be expressed as:

$$v = C_d \sqrt{2g\Delta H} \quad (1)$$

where C_d is the discharge coefficient, g is the gravitational acceleration, and ΔH is the water level difference between the inner canal and the outer sea. To ensure sufficient flushing energy to overcome internal friction across the 2.1 km waterway, a specific threshold of ΔH must be established before the gates are activated.

The operational logic relies on the phase-dependent management of the intake and outlet gates. During the flood tide, the intake gate is opened to draw in oxygen-rich seawater, while the outlet gate remains closed to allow the inner water level to rise. During the ebb tide, the outlet gate is opened to facilitate the discharge of accumulated pollutants toward the open sea. However, to establish a sufficient ΔH to overcome the internal friction and low-velocity characteristics of the 2.1 km canal, both gates must remain closed during the transition periods between tidal phases.

This operational requirement inherently creates a ‘Tidal window gap’—a period of hydraulic stagnation where the advective velocity approaches zero ($v \approx 0$). During this gap, which typically lasts for several hours per tidal cycle, the canal transitions from an advection-dominant state to a reaction-dominant interval. In this phase, the lack of physical transport leads to the rapid depletion of dissolved oxygen (DO) as the system becomes dominated by the biochemical reaction terms (S) associated with anthropogenic nutrient loads. This recurring vulnerability in the passive exchange mechanism provides the fundamental engineering justification for the hybrid intervention framework proposed in this study.

$$\frac{\partial C}{\partial t} \approx S \quad (2)$$

Under these conditions, the rapid depletion of DO is driven by biochemical oxygen demand and sediment oxygen demand (SOD) without the benefit of physical transport or dilution. This recurring vulnerability in the passive exchange mechanism provides the fundamental engineering justification for the hybrid intervention framework—specifically the use of spiral flow aeration and bio-curtains—to artificially modify the reaction term S when $v \approx 0$.

3. Field Observation: Investigation of Mass Mortality and Tidal Flushing Efficacy

3.1. Investigation of the 2022 Mass Mortality Event and Hypoxia Onset

Between July 31 and August 1, 2022, an acute mass fish mortality event occurred within the canal (Figure 6). In response to this acute ecological event, immediate emergency field observations were conducted to investigate the primary cause. In-situ water quality measurements across key cross-sections revealed severely depleted dissolved oxygen (DO) levels, confirming that the event was triggered by the rapid formation of a severe hypoxic to anoxic layer. Crucially, this extreme oxygen depletion was notably observed during the prolonged stagnation period—the ‘Tidal window gap’—required to build a sufficient hydraulic head difference for passive tidal flushing. During this stagnant phase, the absence of flow enabled rapid DO depletion due to the aerobic decomposition of accumulated organic matter, with detailed spatial monitoring results presented in the following section.



Figure 6. Mass fish mortality in 2022 (Photograph courtesy of Yeongdo-gu Office, 2022).

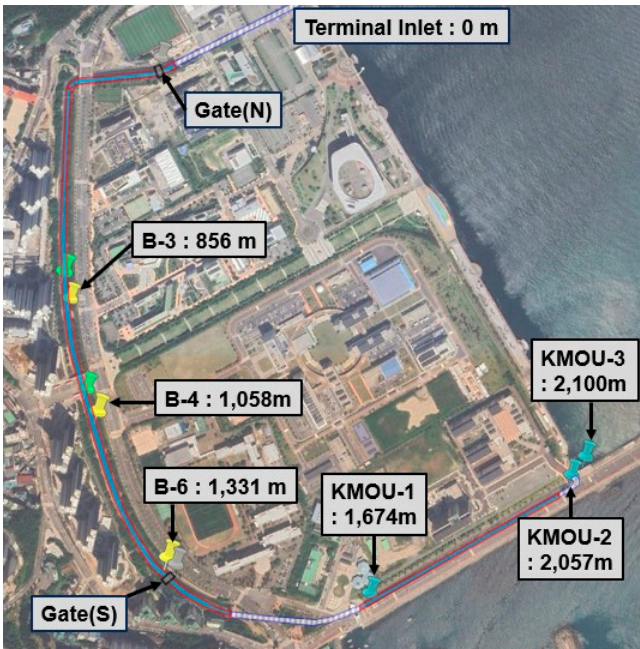
3.2. Spatial DO Profile and Chemical Pollutant Characterization

To evaluate the ecological severity of the hypoxia, the spatial and vertical distribution of the in-situ water quality measurements are presented in Figure 7 and Table 1. To facilitate a direct comparison between physical locations and observed data, Figure 7a delineates the precise longitudinal distances from the Cruise Terminal Inlet (0 m) to the southern terminal (2,100 m). The observed DO levels were classified based on established biological thresholds. According to Diaz and Rosenberg [10], the 2.0 mg/L mark is defined as the conventional threshold for critical hypoxia, below which mass mortality of marine organisms becomes imminent.

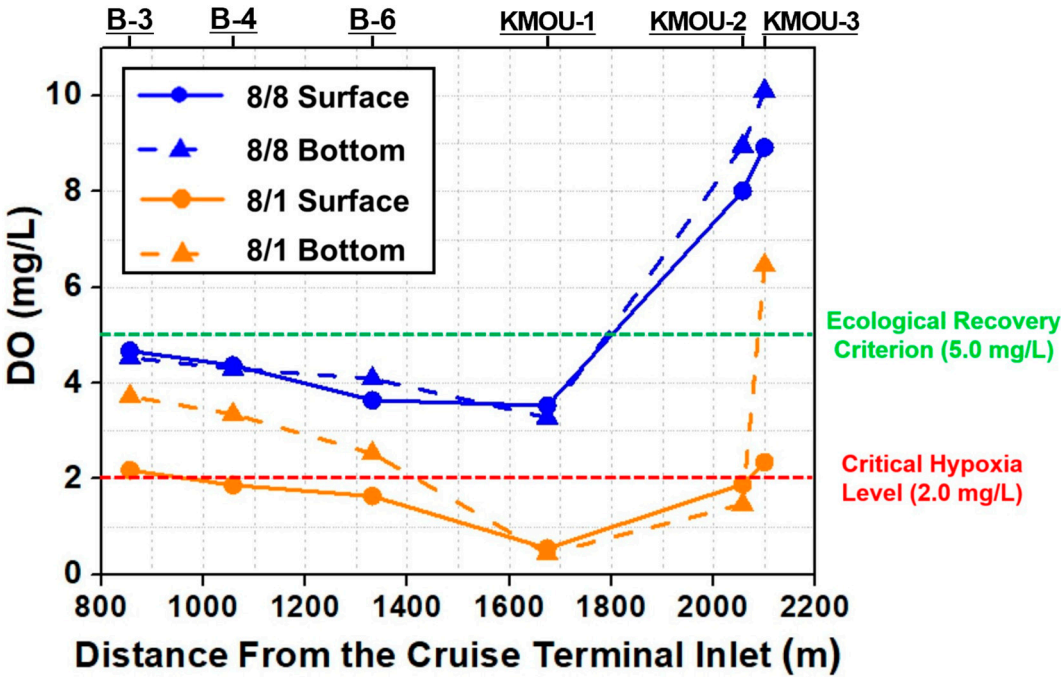
Table 1. In-situ water quality parameters comparing the mass mortality event (August 1) and the post-flushing recovery phase (August 8).

Date	Station	Layer	Depth (m)	Temp (°C)	Salinity (psu)	DO (mg/L)
2022.08.01. (Event)	B-3	Surface	0.0	25.08	26.08	2.18
	B-3	Bottom	1.23	23.33	31.28	3.72
	B-4	Surface	0.0	24.63	29.09	1.87
	B-4	Bottom	1.01	23.36	31.13	3.35
	B-6	Surface	0.0	23.95	28.77	1.64
	B-6	Bottom	1.24	23.42	30.52	2.53
	KMOU-1	Surface	0.0	23.51	29.21	0.55
	KMOU-1	Bottom	1.02	22.91	30.65	0.44
	KMOU-2	Surface	0.0	23.90	30.73	1.89
	KMOU-2	Bottom	0.42	23.89	30.73	1.47
	KMOU-3	Surface	0.0	23.77	30.90	2.35
	KMOU-3	Bottom	1.63	22.46	31.93	6.46
2022.08.08.	B-3	Surface	0.0	23.40	29.48	4.67

(Recovered)	B-3	Bottom	0.47	21.17	31.56	4.53
	B-4	Surface	0.0	23.57	29.28	4.37
	B-4	Bottom	0.37	22.65	30.58	4.30
	B-6	Surface	0.0	23.19	30.31	3.64
	B-6	Bottom	0.72	22.98	30.62	4.09
	KMOU-1	Surface	0.0	23.36	29.80	3.53
	KMOU-1	Bottom	0.90	22.62	31.00	3.28
	KMOU-2	Surface	0.0	21.13	32.42	8.01
	KMOU-2	Bottom	1.10	19.98	32.85	8.95
	KMOU-3	Surface	0.0	20.21	32.76	8.92
	KMOU-3	Bottom	1.42	19.00	33.06	10.10



(a)



(b)

Figure 7. Spatial identification of monitoring stations and longitudinal DO profiles. (a) Satellite imagery of the Dongsam tidal canal with cumulative distances from the Cruise Terminal Inlet (0 m) to the southern terminal (2100 m). (b) Spatial distribution of dissolved oxygen (DO) along the longitudinal axis, comparing the mass mortality event (August 1) and normal condition (August 8).

As illustrated in the longitudinal profile (Figure 7b) and detailed in the in-situ data (Table 1), a distinct vertical DO gradient was observed across the canal during the stagnation period (August 1). This is primarily attributed to the ‘Tidal window gap,’ during which closed sluice gates completely blocked tidal exchange. This hydraulic stagnation prevented vertical mixing, resulting in severe vertical stratification. Consequently, the bottom-layer DO concentration recorded at the downstream terminal station (KMOU-1) plummeted to 0.44 mg/L. This value falls directly into the ‘Critical hypoxia’ or ‘Anoxia’ category, providing definitive evidence for the direct cause of the mass fish kill event.

Laboratory analysis of water samples collected from the primary discharge points (D-series) reveals significant concentrations of organic and nutrient pollutants, which serve as the fundamental drivers of dissolved oxygen depletion within the canal. As summarized in Table 2, the measured chemical oxygen demand (COD) at points D-2 and D-3 reached 9.18 mg/L and 10.11 mg/L, respectively.

Table 2. Laboratory analysis results of primary discharge points (D-series) indicating high concentrations of organic and nutrient pollutants.

Analysis points	COD (mg/L)	TN (mg/L)	TP (mg/L)
D-2	9.18	6.62	0.78
D-3	10.11	12.50	2.89

These elevated COD levels indicate a high organic load originating from urban runoff, which exerts substantial oxygen demand during microbial decomposition. Furthermore, exceptionally high concentrations of total nitrogen (TN) (up to 12.50 mg/L) and total phosphorus (TP) (up to 2.89 mg/L) were observed at D-3, characterizing the intermittent effluent as a potent source of nutrient pollution.

The influx of these high-concentration pollutants is critical to understanding the formation of anoxic layers. During the ‘Tidal window gap’ – the stagnant phase when sluice gates remain closed – these pollutant plumes from the D-series outfalls are trapped and accumulate within the internal canal body. In the absence of tidal flushing, the high organic load promotes rapid oxygen consumption, particularly in the bottom layer where organic particulate matter tends to settle, and even in the surface layer where the aerobic decomposition of dead fish occurs. This mechanism is clearly evidenced by the critical hypoxia observed in the bottom-layer data in Table 1, where DO concentrations plummeted to as low as 0.44–0.55 mg/L. Therefore, the laboratory results from the D-series outfalls provide definitive chemical evidence that these urban discharges are the primary catalysts for the acute hypoxia threatening the canal’s aquatic ecosystem.

3.3. Efficacy of Sustained Tidal Exchange and Justification for Active Intervention

Following the mass mortality event, an intensive operational intervention was initiated, consisting of continuous seawater exchange leveraging maximum tidal differences over a one-week period. As shown in the August 8 profile (Figure 7b), this active tidal flushing successfully disrupted the vertical stratification, transitioning the canal into a ‘well-mixed’ state with minimal concentration differences between the surface and bottom layers.

However, while the overall DO levels exhibited a clear upward trend approaching the 5.0 mg/L ecological recovery target, the recovered data in Table 1 shows that several stations remained within the ‘Sub-lethal stress’ range (2.0–4.6 mg/L), as identified by Vaquer-Sunyer and Duarte [11]. This suggests that physiological stress on the aquatic community might persist, and the quantitative

decrease of accumulated organic and nutrient levels (e.g., COD, TN, and TP) after the intervention requires further empirical validation.

Furthermore, a critical observation during the crisis was the localized extreme hypoxia at station KMOU-1, which was heavily influenced by legacy organic sediments within the covered culvert that had not been dredged at the time. Although recent comprehensive dredging has removed these internal oxygen-demanding sediments, this previous failure highlights the inherent vulnerability of the canal to 'dead zone' formation under stagnant conditions.

This observation yields a dual conclusion: while tidal flushing is undeniably effective for water purification when active, the inherent reliance on passive tidal differences fundamentally fails to prevent acute ecological disasters during 'Tidal window gaps'. The temporary restoration of water quality via one week of forced flushing highlights a reactive, rather than preventative, management paradigm. Therefore, to ensure continuous ecological stability and actively break down vertical stratification during stagnation, it is imperative to implement hybrid active systems—such as localized spiral aeration (to induce forced hydrodynamic mixing) and nutrient-intercepting vertical bio-curtains (to mitigate D-series effluents)—that operate independently of the natural tidal cycle.

4. Proposed Hybrid Framework for Water Quality Improvement

4.1. Aeration System Design

4.1.1. Rationale and Theoretical Background

The primary cause of the 2022 mass fish mortality event was the rapid depletion of dissolved oxygen (DO) during the stagnant 'Tidal window gap'. Therefore, an active aeration system is introduced as the most direct and critical intervention. Its primary function is to artificially modify the reaction term (S) in the mass balance equation, injecting sufficient oxygen to maintain the DO concentration above the ecological survival threshold (typically 2.0 to 3.0 mg/L) during advection-free intervals.

The oxygen transfer mechanism is fundamentally governed by the two-film theory, expressed through the volumetric mass transfer coefficient ($K_L a$). It is important to note that $K_L a$ is not a single empirical constant, but rather the product of two distinct physical parameters: the liquid-film mass transfer coefficient (K_L) and the specific interfacial area (a). Here, K_L reflects the liquid-phase resistance, which dictates the transfer rate of low-solubility gases such as oxygen. The variable a signifies the total gas-liquid contact area per unit volume m^{-1} .

In shallow urban canals, conventional bottom-up aeration is highly inefficient because the vertical ascent time of the bubbles is too short to allow significant oxygen dissolution. To maximize $K_L a$ and overall aeration efficiency, the geometric trajectory of the bubbles must be structurally extended to increase both the turbulence-induced mass transfer coefficient (K_L) and the total contact area (a).

4.1.2. Optimization of Effective Width, Longitudinal Spacing, and Injection Angles

Instead of the conventional central channel installation method, the diffusers in this framework are strategically mounted along the lateral walls of the canal to induce a continuous spiral (vortex) circulation. The hydrodynamic superiority of this wall-mounted configuration over central placement lies in the scale of the generated transverse mixing cells and the preservation of hydraulic conveyance. When diffusers are placed in the center of a shallow channel, they generate two smaller, symmetrical counter-rotating cells. This symmetric configuration causes bubbles to ascend rapidly along the vertical axis, severely limiting their residence time and overall air-water contact [12].

In contrast, an asymmetric, wall-mounted configuration generates a strong localized updraft along the installation wall, forcing a single, macro-scale transverse circulation cell that spans the entire channel width (Figure 8).

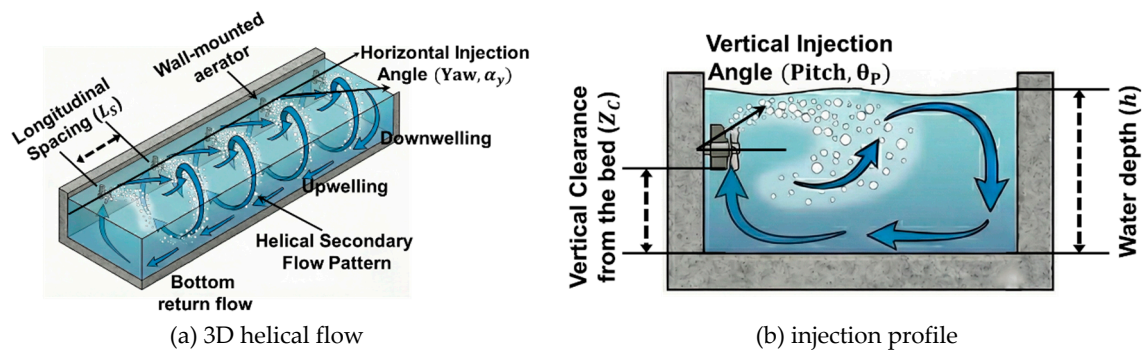


Figure 8. Conceptual diagram of spiral flow aeration. Note: The conceptual backgrounds were visualized with the assistance of Gemini (Google).

As demonstrated in hydrodynamic evaluations of spiral aeration systems [13], this unilateral updraft significantly extends the lateral travel distance and the residence time of the bubbles before they reach the surface, thereby maximizing the specific interfacial area (a) and the volumetric mass transfer coefficient (K_La). Furthermore, from a hydraulic engineering perspective, placing the hardware flush against the lateral walls keeps the main channel completely free from physical obstructions. This ensures that the primary tidal flushing mechanism remains hydrodynamically unimpeded, avoiding the increased boundary friction and debris entanglement risks inherently associated with central channel installations [14]. Through a comprehensive review of the literature, specific design considerations for implementing a single-sided, wall-mounted aeration system were derived as follows:

- **Layout and O&M Optimization based on Effective Mixing Width (W_{eff}):**
The geometric reach of a single spiral circulation cell—defined as the effective mixing width ($W_{eff} \approx 2.5h$)—is the primary determinant for the spatial configuration of the aeration units. To ensure uniform dissolved oxygen (DO) distribution while preventing energy loss through hydraulic interference, this framework proposes a three-tier layout strategy governed by the relationship between the channel width (W) and effective mixing width (W_{eff}):
 - **Single-sided Configuration ($W \leq W_{eff}$):** For narrow channels where the total width does not exceed the reach of a single circulation cell, a single-sided wall installation is prioritized. This setup induces a single, large-scale circulation roll that covers the entire transverse section. By avoiding opposing flows, it maximizes energy efficiency and provides a continuous ‘oxygen refuge’ for mobile aquatic organisms during acute hypoxic events [15,16].
 - **Bilateral Configuration ($W_{eff} < W \leq 2W_{eff}$):** When the channel width exceeds the reach of a single cell but remains within the combined reach of two, diffusers are mounted on both opposing walls. This ensures that the oxygen-rich plumes from both sides converge at the center, eliminating potential ‘dead zones’ in the mid-channel [14].
 - **Bilateral Staggered Configuration ($W > 2W_{eff}$):** For wide urban canals where W significantly exceeds the dual reach, a staggered arrangement is required. By offsetting the units longitudinally, the system generates a continuous, zig-zag spiral advection pattern. This configuration prevents the short-circuiting of flows and promotes intensive transverse mixing across the entire width, effectively extending the hydraulic retention time (HRT) [17].
 - **Practical Benefits for Operations and Maintenance (O&M):**
Beyond hydrodynamic optimization, the wall-mounted configuration (whether single or bilateral) offers significant practical advantages over conventional center-channel installations. Unlike bed-mounted systems that require specialized maritime equipment or divers for inspection, wall-mounted diffusers are directly accessible from the canal bank or walkway. This accessibility allows for simplified routine maintenance—such as cleaning

fine-pore membranes or replacing damaged modules—using standard reach tools. By eliminating the need for heavy machinery and minimizing underwater operations, this configuration reduces operational downtime and the total life-cycle cost of the infrastructure [12].

- **Optimization of Longitudinal Spacing (L_s) for Targeted Spiral Flow Stability:**

To maintain a contiguous ‘oxygen refuge’ corridor along the single-sided wall during the advection-free ‘tidal window gap,’ the longitudinal spacing (L_s) between adjacent aeration units must be optimized. Traditionally, environmental engineering guidelines for static mixing focus on the zone of aeration influence (ZAI), typically limited to 4–6 m in shallow waters [12]. However, maintaining the hydrodynamic stability of a macroscopic spiral vortex requires a broader geometric consideration beyond simple point-source oxygenation.

Hydrodynamic studies suggest that the rotational momentum of an induced spiral cell begins to decay as it travels longitudinally. As emphasized by Eby and Crowder [15], re-energizing the flow field through the continuous input of momentum is crucial for maintaining the continuity of the vortex structure and preventing its premature dissipation. To ensure this re-invigoration, this study establishes a spacing criterion of $L_s = 10 \times W_{eff}$ (where $W_{eff} \approx 2.5h = 5.0$ m). This 10-fold scaling of the effective mixing width ensures that the spiral flow is reinforced before transverse momentum dissipates, creating a stabilized aerobic corridor. By concentrating the intervention in targeted segments rather than across the entire 2.1 km length, the system optimizes energy efficiency while providing a robust ecological refuge where stagnation and pollution loads are most critical.

- **Geometrical Constraints and Lateral Coverage in Wide Canals:**

Despite the optimization of longitudinal spacing, the lateral reach of the induced spiral flow is inherently constrained by the channel’s aspect ratio (W/h). Standard hydrodynamic principles suggest that a stable single circulation cell is typically maintained up to an aspect ratio of 2.5 ($W_{eff} \approx 2.5h$). In urban canals where the width (W) can reach 20–30 m against a shallow depth ($h \approx 2$ m), aspect ratios as high as 10 to 15 cause the transverse momentum of the surface jet to dissipate before reaching the opposite embankment, leaving stagnant dead zones. To ensure full-section coverage in these high-aspect-ratio environments, this study proposes a staggered (zigzag) configuration on both embankments for canals exceeding twice the effective mixing width ($W > 5h$), supplemented by increased aeration intensity to sustain lateral momentum. These strategic adjustments prevent flow detachment and ensure that the spiral vortex re-invigorates the entire canal width, forming the basis for the site-specific design parameters detailed in Section 5.

- **Vertical Clearance from the Bed ($Z_c = 0.2h$):** The vertical clearance between the diffusers and the canal bed is a decisive factor in preventing secondary pollution via sediment resuspension. Historically, conventional wastewater treatment standards, as established by Tchobanoglous et al. [12], recommend a lower clearance of approximately 0.1 to maximize bubble contact time and enhance oxygen transfer efficiency (OTE) in controlled, often concrete-lined environments.

However, in urban tidal canals characterized by silty and organic-rich sediments, such proximity can be counterproductive due to severe benthic scouring. Recent hydrodynamic investigations on shallow systems have demonstrated that if the aeration jet is positioned too close to the bed, the high-velocity kinetic energy can overcome the critical shear stress of the sediment, triggering resuspension [18].

By comparing the efficiency-driven baseline of Tchobanoglous et al. [12] with the protection-focused hydrodynamic evaluations of Unger and Hager [18], this study proposed that an optimized threshold of $0.2 h$ (0.4 m for the 2.0 m depth) is necessary for these specific environments. This increased offset serves as a hydrodynamic buffer, ensuring that the kinetic energy of the initial air jet dissipates through entrainment and mixing before reaching the benthic interface. Consequently, this configuration effectively suppresses internal nutrient

loading and turbidity increases while ensuring the lower water column remains sufficiently oxygenated.

- **Longitudinal Setback Distance (L_{sb}) from Tidal Gates for Structural Safety:**

While the aeration system is explicitly designed for operation during the stagnant ‘Tidal window gap’ when the gates are closed, its primary engineering constraint is the structural resilience of the hardware during active tidal exchange. Because the canal utilizes bi-directional tidal gate operation, the internal infrastructure is exposed to severe hydrodynamic forces. Particularly during the flood-tide phase, when the bottom-hinged gates are lowered to induce inward artificial flushing, the established maximum potential head difference (ΔH_{max}) generates a sudden, supercritical overflow into the canal. This process creates a zone of flow separation characterized by intense downstream turbulence, extreme bed shear stress, and macro-turbulent eddies immediately adjacent to the gates.

Empirical engineering evaluations have documented cases where instream appurtenances and bed-mounted structures installed in such zones have suffered catastrophic structural failure—including complete detachment and foundation collapse—due to massive local scour and extreme hydrodynamic forces [17,18]. To mitigate these risks of physical destruction, a strict longitudinal setback distance (L_{sb}) must be enforced. Based on standard hydraulic design principles for energy dissipation zones, the first aeration unit should be positioned entirely outside the turbulent wake. Following energy-based engineering principles, this necessitates a longitudinal offset of at least 15 times the maximum tidal range difference (ΔH_{max})—which, as detailed in Section 2.1, reaches a maximum tidal range of approximately 1.5 m. This ensures a L_{sb} of 22.5 m (for $\Delta H = 1.5$ m), placing the equipment within a stabilized open-channel flow regime where the kinetic energy from the inward flushing has been sufficiently dissipated [14,17].

Beyond structural protection, this strategic setback provides a secondary benefit as an auxiliary ice-suppression system during winter months. The thermal advection and surface agitation induced by air bubble plumes are well-established mechanisms for preventing the formation of solid ice sheets around hydraulic structures [19]. By inducing a continuous 3D spiral circulation, the system effectively transports relatively warmer benthic water toward the gate area even during stagnant periods. This process significantly mitigates ice-induced mechanical stress on the gate mechanisms and preserves the operational readiness of the infrastructure year-round.

- **Optimization of Diffuser Injection Angles (Pitch and Yaw)** The orientation of the diffusers governs the efficiency and stability of the spiral flow. Based on hydrodynamic evaluations of spiral aeration systems and transverse mixing in shallow flows, the injection angles must be carefully calibrated in two planes to maximize the oxygen transfer mechanism:

- Horizontal angle (Yaw, α_y): Instead of injecting air strictly perpendicular to the canal wall, the nozzles are oriented with a downstream bias of 30°-45° relative to the transverse axis. In stagnant conditions where no background longitudinal velocity exists, this bias is essential to artificially generate longitudinal momentum. This transformation of the simple transverse roll into a helical (corkscrew) flow path ensures that oxygen-rich water is effectively transported toward remote “dead zones” near the barrages, expanding the reach of the oxygen refuge [20].
- Vertical angle (Pitch, θ_p): The diffusers are oriented with an upward trajectory of 15°-25° from the horizontal plane. This upward pitch is strategically designed to prevent the aeration jet from directly impacting the canal bed. By guiding the bubble plume along a rising diagonal path, the system maximizes the residence time of bubbles in the water column and promotes a large-scale transverse circulation cell [13].

4.2. Vertical Bio-Curtain Design

4.2.1. Theoretical Framework and Bio-curtains Concept

Vertical bio-curtains represent a high-efficiency adaptation of Floating Treatment Wetlands (FTWs), specifically engineered to intercept and sequester nutrient fluxes in advection-dominated urban canals. Traditional FTW designs often necessitate substantial surface area coverage—typically estimated at 10% of the total water body area—to achieve significant nutrient reduction through passive uptake [21]. However, in narrow urban tidal canals like the Dongsam tidal canal, such extensive horizontal coverage is often impractical. Large-scale floating mats can lead to aesthetic impairment of the urban promenade and cause a significant reduction in flow velocity, interfering with the canal’s primary function of tidal flushing.

Furthermore, dispersed horizontal systems are frequently subject to ‘hydraulic bypass,’ where the majority of contaminated water flows underneath the root mat, significantly limiting the contact time between the rhizosphere and the pollutants. To overcome these limitations, the vertical bio-curtain configuration concentrates the vegetation into a high-density vertical matrix. This design, synergized with the spiral flow generated by the aeration system (Section 4.1), forces the water column to permeate directly through the dense root-biofilm structure. This maximizes the interfacial contact area and leverages physical filtration, plant assimilation, and microbially-mediated transformations simultaneously [22,23]. The empirical effectiveness of this concentrated “curtain” effect has been validated by several key studies. Previous research [24,25] demonstrated that systems with optimized vertical root architectures can achieve nutrient removal efficiencies exceeding 60% even in active flow environments, while Borne et al. [21] established that the vertical root mat functions as a physical “bio-filter,” effectively trapping suspended solids and particulate nutrients.

Integrating these foundations into the canal requires a site-specific engineering approach that leverages the synergy between aeration and biological filtration. Specifically, the integration of micro-bubbles serves a dual purpose: it prevents the formation of anaerobic dead zones within the dense root matrix during stagnant periods and actively supplies oxygen to the biofilm, thereby accelerating the microbial degradation of organic pollutants. Given the canal’s relatively shallow depth, the bio-curtain must be engineered to remain structurally resilient against tidal forces while maximizing synergy with the spiral flow generated by the aeration system (Section 4.1). This necessitates the rigorous optimization of key physical parameters, such as root immersion depth (D_r) and planting density (ρ_p), to ensure reliable performance within this dynamic tidal environment [27].

4.2.2. Ecological Selection Criteria

To ensure the versatility of the proposed hybrid framework, it is essential to categorize suitable aquatic vegetation based on climatic conditions. The metabolic activity of the rhizosphere and its associated biofilm—which directly governs the nutrient removal efficiency—is predominantly regulated by water temperature. Table 3 summarizes the eco-physiological thermal ranges—delineating both the absolute survival limits and the optimal windows where biomass growth and root-zone nutrient assimilation peak—alongside the documented total nitrogen (TN) and total phosphorus (TP) removal efficiencies for representative aquatic species.

Table 3. Eco-physiological thermal ranges and documented nutrient removal efficiencies (TN and TP) of representative bio-curtain vegetation [22,23,28–36].

Climate Zone	Representative Species	Survival Range (°C)	Optimal Range (°C)	Removal Efficiency of TN (%)	Removal Efficiency of TP (%)
Cold	<i>Phragmites australis</i>	-20 to 45 [28]	15–30 [30]	40–70 [22]	30–50 [22]
	<i>Typha latifolia</i>	-15 to 40 [29]	15–30 [29]	45–75 [31]	45–75 [31]
Temperate	<i>Iris pseudacorus</i>	-15 to 35 [32]	15–30 [32]	50–80 [33]	40–70 [33]
Tropical	<i>Canna indica</i>	-5 to 40 [23]	25–35 [34]	60–85 [34]	50–80 [34]
	<i>Cyperus papyrus</i>	10 to 40 [23]	20–35 [35]	55–80 [36]	45–75 [36]

As detailed in Table 3, the vegetation selection is primarily categorized by climatic thermal ranges to ensure global applicability. Crucially, regardless of the climate zone, all proposed species (e.g., *Phragmites australis*, *Iris pseudacorus*, and *Canna indica*) share a strong capacity for hydroponic adaptation. This physiological trait is essential for application in artificial waterways like the Dongsam tidal canal, which features a concrete bed. Supported by the buoyant structure, these emergent macrophytes develop extensive fibrous root systems directly within the water column. This soil-less adaptation allows the plants to extract essential nutrients (nitrogen and phosphorus) entirely from the eutrophic canal water, ensuring robust survival and maximizing phytoremediation efficiency without requiring physical anchorage to the canal bed.

Furthermore, the selected vegetation for the bio-curtain inherently forms compact, shallow root matrices (typically extending 0.4 to 0.8 m) in eutrophic waters. This natural physiological trait ensures that the 1.2 m root depth constraint is maintained without the need for labor-intensive periodic pruning. Such a low-maintenance, passive design significantly enhances the feasibility and sustainability of the framework, making it particularly viable for implementation in developing regions with limited operational resources.

By categorizing these empirically validated plants into cold, temperate, and tropical zones, the framework provides a robust guideline for optimizing bio-curtain performance across diverse geographical environments. This ecological classification directly informs the climate-adaptive scaling of planting densities (ρ_p) and root immersion depths (D_r) detailed in Section 4.2.3. By aligning biological selection with these quantitative engineering parameters, the system ensures that the bio-curtain maintains its structural and metabolic integrity under varying thermal and hydrodynamic stresses.

4.2.3. Optimization of Root Depth (D_r) and Density (ρ_p)

- **Optimized Root Depth (D_r):** The effective root depth (D_r) is a fundamental determinant of interception efficiency within the canal system. For the target canal, which is distinguished by an operational depth (h) of approximately 2.0 m during the stagnant 'Tidal window gap', D_r was scaled using a dimensionless immersion ratio that relates the root depth to the total water depth.

In floating treatment wetlands (FTWs) and similar vegetated aquatic treatment systems, pollutant removal primarily occurs within the plant root zone suspended in the water column, where plant surfaces and associated biofilms promote filtration, adsorption, and microbial degradation processes [27,37]. Effective treatment therefore requires sufficient overlap between the water column and the vegetated root zone while avoiding hydraulic bypass, where a portion of the flow passes beneath the treatment layer without interacting with the roots [38]. Reported root depths of floating wetland vegetation typically range from several tens of centimeters to approximately 1 m depending on plant species and growth conditions [27,38].

Considering these typical root-length scales and the need to maintain both treatment interaction and hydraulic conveyance, a representative immersion ratio defined as

$$r_d = D_r/h \quad (3)$$

was adopted as a design parameter. An immersion ratio of approximately 0.6 was selected as a balanced configuration in which a majority of the water column interacts with the vegetated root zone while a lower free-flow layer remains available for hydraulic transport. Ratios substantially lower than this would reduce pollutant–root contact within the treatment zone, whereas excessively large ratios could increase flow resistance and promote hydraulic blockage within the confined canal geometry. For the operational canal depth of $h \approx 2.0$ m, this ratio yields an effective root depth of

$$D_r = r_d \times h = 0.6 \times 2.0 = 1.2 \text{ m} \quad (4)$$

Importantly, because this parameter is expressed as a ratio between root depth and water depth rather than an absolute depth, the same design criterion can be consistently applied to canals with different water depths by proportionally adjusting D_r .

It is important to note that during active flushing, when the water level reaches its absolute minimum (e.g., ~0.74 m) and flow velocities peak, the bio-curtain does not act as a rigid barrier. The highly flexible nature of the living fibrous root matrix allows it to hydrodynamically reconfigure and deflect downstream. This flexibility prevents excessive flow resistance and structural damage that would otherwise occur if a rigid 1.2 m structure were subjected to shallow, fast-moving water. Simultaneously, the deflected root matrix acts as a physical “straining sweep” across the reduced water column, effectively trapping suspended particles and polishing the discharge water without compromising the canal’s primary flushing capacity.

- **Planting Density (ρ_p) and Climate-Adaptive Scaling:** The areal planting density (ρ_p) is a critical factor governing the volumetric reactive surface area available for the establishment of periphytic biofilms. A higher density configuration fundamentally enhances the surface area-to-volume (SA/V) ratio, thereby promoting the development of root-associated biofilms that play a key role in nutrient removal processes in floating treatment wetlands [27]. According to comprehensive reviews of floating treatment wetlands (FTWs) [25,39], operational densities typically vary widely depending on target species and environmental conditions. Rather than applying a universal fixed value, this framework recommends adaptively scaling the density within a continuous operational spectrum (spanning approximately 12 to 32 plants/m²) based on local climatic constraints:
 - **Cold Zones (12-16 plants/m²):** Operating near the lower end of this density spectrum is recommended. This more conservative spacing maintains essential hydrodynamic porosity and prevents severe root overcrowding and anaerobic rot during prolonged winter dormant phases, ensuring plant survival when metabolic rates and oxygen translocation are minimal.
 - **Temperate Zones (16-24 plants/m²):** A median optimization approach is proposed as an optimal baseline. This range ensures rapid canopy closure and maximizes nutrient assimilation during the growing season, while maintaining sufficient spacing to prevent localized root-zone hypoxia during seasonal transitions.
 - **Tropical Zones (24-32 plants/m²):** Densities approaching the upper operational limits can be sustainably employed. This ultra-high-density approach fully maximizes the SA/V ratio, capitalizing on year-round rapid biomass growth and elevated microbial kinetics to effectively manage the massive organic loads typical of warm, non-dormant environments.
 - By concentrating the vegetation into a vertical curtain rather than dispersing it into horizontal mats, the system achieves a superior biofilm-to-water contact ratio by ensuring that the advective flow passes through the densest part of the rhizosphere. This configuration effectively maximizes the biochemical treatment capacity within a limited footprint, adhering to the principle that maximizing the interfacial contact area is critical for efficient pollutant transformation [23]. By integrating these vertical (D_r) and horizontal (ρ_p) parameters, the bio-curtain functions as a globally adaptable, climate-sensitive filtration system tailored for high-energy urban tidal environments.

4.2.4. Structural Support and Material Considerations: Vertical Guide Rails

The implementation of a robust vertical support system is the primary requirement for ensuring the physical stability and functional positioning of modular bio-curtains. Field applications in urban tidal environments [40] have demonstrated that vertical guide rails are essential for securing floating modules against tidal fluctuations and hydraulic drag, preventing them from drifting or being washed away during peak flow events.

In selecting materials for these rails, long-term structural integrity in chemically aggressive environments must be prioritized. Conventional metallic materials often encounter significant challenges in urban waterways where untreated sewage is frequently discharged, as high concentrations of sulfides and organic acids can lead to rapid degradation.

To mitigate these risks, fiber-reinforced polymer (FRP) is proposed as a high-durability alternative. Previous research [41] confirmed that FRP composites exhibit excellent chemical resilience, making them highly suitable for aggressive environments such as sewage systems, while their long-term structural stability and resistance to environmental degradation have been further validated by Hollaway [42]. Furthermore, FRP provides absolute resistance to chloride-induced corrosion, making it highly effective in estuarine and marine conditions. The reliability of FRP composites has been further validated by their extensive application in coastal and industrial infrastructure, particularly in the structural repair of marine piles [43]. These proven performance records in harsh marine environments suggest that FRP-based guide rails offer a sustainable and low-maintenance solution for the proposed system.

5. Case Studies and Strategic Implementation

5.1. Strategic Application to the Dongsam Tidal Canal

In consideration of the in-situ monitoring results from Section 3 and the engineering optimization principles established in Section 4, this section proposes a strategic application of the hybrid system to the Dongsam tidal canal. This case study serves as a “prototype validation,” where the design thresholds optimized for sediment protection and spiral flow continuity are specifically tailored to the canal’s unique geometric ($h \approx 2.0$ m, $W \approx 10$ m) and hydrodynamic conditions.

The configuration focuses on the longitudinal open-channel reaches (B and KMOU series), where stagnation-induced hypoxia was empirically identified during the “Tidal window gap.” By integrating site-specific spatial vulnerabilities with the proposed technical framework, this application seeks to establish a contiguous ‘oxygen refuge’ corridor within the most stagnant reaches, ensuring ecological survival during critical periods of water quality degradation.

5.1.1. Optimization of Placement: W_{eff} and Oxygen Refuge Strategy

Following the placement optimization criteria established in Section 4.1.2, the aeration system was dimensionally scaled for the Dongsam tidal canal. With an operational baseline depth (h) of 2.0 m, the effective mixing width ($W_{eff} \approx 2.5h$) is calculated as 5.0 m. Although the canal’s total width ($W = 10$ m) is twice this W_{eff} , a single-sided configuration was selected to induce a large-scale, unified transverse circulation cell.

In this setup, the upward bubble plume is intended to generate a primary mixing zone along the installation wall, while the resulting transverse pressure gradient drives a return flow that reaches the opposite bank. Hydrodynamic estimations suggest that while the dissolved oxygen (DO) concentration may exhibit a lateral gradient, it is anticipated to remain above the acute lethal threshold (> 3 mg/L) across the full width, effectively transforming the 10 m reach into a viable aerobic corridor. To satisfy the 500 m² minimum oxygen refuge requirement, the aeration units are strategically deployed over a 50 m longitudinal stretch. This optimized scaling is proposed to establish a functional refuge footprint that ensures ecological survival during the ‘Tidal window gap’ while maximizing cost-efficiency by eliminating redundant bilateral infrastructure.

5.1.2. Layout of the Spiral Aeration Units: Dual-Scale ‘Stepping-Stone’ Refuge

To physically realize this aerobic corridor while ensuring connectivity across the 2.1 km canal, a multi-node ‘stepping-stone’ refuge system is proposed, addressing the behavioral avoidance thresholds and physiological escape limits of aquatic organisms under hypoxic stress [44]. The layout is bifurcated into two distinct scales to balance ecological efficacy with energy efficiency:

- **Type I: Ecological Refuge Nodes (B-4, B-6, KMOU-1):**

Targeting hydrodynamic ‘dead centers,’ these primary nodes are designed to provide the required 500 m² survival corridor. Based on the established spacing criterion of $L_s = 10 \times W_{eff}$ (50m for the 10 m width), a cluster of two aeration units is sequentially deployed per node. Since the induced helical momentum is expected to decay after traveling approximately 10 times the effective mixing width, the second unit is strategically positioned at the 50 m mark to re-energize the vortex structure.

This 2-unit relay system is intended to maintain a continuous 50 m aerated reach, aiming to establish the 500 m² functional footprint (10 m width $\times$ 50 m length) required for a robust ecological refuge.

- **Type II: Targeted Control Nodes (D-2, D-3, Gates):**

At point-source inflows and gate-inland buffers, the objective shifts toward active hydraulic exchange within stagnant water masses during gate closure periods. A single aeration unit is utilized to establish an intense localized recirculation zone. By inducing turbulent vertical plumes and transverse circulation, this configuration is intended to overcome water stagnation and disrupt the formation of inactive boundary layers. This hydrodynamic activation is anticipated to maximize the frequency of pollutant-root contact with the adjacent bio-curtains during the holding period, thereby enhancing overall treatment efficiency within the scheduled residence time while strictly minimizing unnecessary energy expenditure.

5.1.3. Hydrodynamic Safety and Operational Resilience

To aim for operational longevity and prevent potential secondary water quality degradation, precise vertical and longitudinal positioning criteria are proposed for the canal:

- **Vertical Clearance and Submergence:** The diffusers are mounted at a fixed elevation of 0.4 m above the canal bed—corresponding to 20% of the operational baseline depth ($h = 2.0$ m)—to minimize the resuspension of fine benthic sediments [18]. Even at the absolute minimum water level (0.74 m on Feb 20th, 2022), a 0.34 m water cover (the submergence depth from the water surface to the diffuser unit) is expected to be maintained, which is anticipated to support uninterrupted operation without atmospheric exposure or surface splashing. Consequently, the proposed diffuser elevation provides a hydrodynamically stable configuration capable of maintaining continuous aeration performance under the variable water-level conditions characteristic of micro-tidal canal systems.
- **Longitudinal Setback Distance (L_{sb}):** To protect the mechanical units from high-velocity flushing jets during gate operations, units positioned near the tidal gates maintain a proposed setback distance (L_{sb}) of 22.5 m. This value is derived from the hydrodynamic safety criterion of $15 \times \Delta H_{max}$, based on the maximum head difference ($\Delta H_{max} = 1.5$ m) established in Section 2.1 [17].
- **Winter Ice Suppression Synergy:** Despite this structural setback, the gate-adjacent Type II single-unit systems are anticipated to function as auxiliary ice-suppression mechanisms. Since the 22.5 m offset is within the effective reach of the localized spiral mixing generated by the unit, the forced advection of warmer, brackish benthic water is expected to reach the gate infrastructure. This continuous thermal transport is intended to help disrupt the static boundary layer, aiming to protect the critical gate mechanisms from frazil ice formation and potentially mitigating the risk of mechanical failure caused by localized freezing [19].
- **Aeration Injection Angles:** Following the optimization criteria established in Section 4, the diffuser units for the Dongsam tidal canal were configured with a horizontal angle of 45° and a vertical angle of 20°. This specific alignment is adopted to maximize the effective spiral mixing width (W_{eff}) and facilitate vertical oxygen transport throughout the water column, while ensuring that the jet trajectory remains sufficiently clear of the canal bed to prevent localized benthic scouring.

5.1.4. Geometric Optimization, Density Configuration, and Aesthetic Integration

The physical dimensions and internal planting density of the bio-curtains are optimized to simultaneously ensure pollutant interception efficiency, biological treatment capacity, and landscape value, specifically tailored to the environmental and social conditions of the canal:

- **Optimized Immersion and Bottom Clearance:** Based on the operational baseline depth ($h = 2.0\text{ m}$), an optimized immersion ratio of 0.6 (equivalent to a 1.2 m root depth) is applied to intercept 60% of the water column. This configuration is strategically designed to maximize nutrient interception while maintaining a 0.8 m bottom gap. This clearance is designed to serve as a functional bypass zone, aiming to minimize hydrodynamic drag forces on the bio-curtain and ensure the preservation of hydraulic conveyance within the canal during high-velocity tidal flushing events.
- **Optimized Vegetation Density (ρ_p):** Within the temperate thermal window of the target site ($-15\text{ }^{\circ}\text{C}$ to $35\text{ }^{\circ}\text{C}$), *Iris pseudacorus* was selected as the primary species for its exceptional metabolic adaptability and salinity tolerance. Aligning with the temperate scaling matrix established in section 4 (16–24 plants/m²), a median-high density of 20 plants/m² is implemented for the Dongsam tidal canal. This configuration is aimed at achieving a surface area-to-volume (SA/V) ratio estimated to be 3 to 5 times higher than traditional, scattered floating mats [27]. By increasing the available attachment surface for nitrifying biofilms and the frequency of root-water contact, this strategy is expected to enhance the potential for biofilm-mediated nutrient assimilation and suspended solid interception without inducing localized root-zone hypoxia.
- **Aesthetic Integration and Landscape Value:** As the canal serves as a recreational promenade, the bio-curtains are proposed to provide visual masking for unsightly infrastructure, such as sewage outfall pipes near D-2 and D-3. This nature-based integration is intended to improve landscape aesthetics and public perception, potentially enhancing the overall recreational experience for waterfront visitors and promoting the social acceptance of urban ecological restoration projects.

5.1.5. Adaptive Anchoring and Operational Resilience of Bio-Curtains

- **FRP Guide Rail System for Tidal Adaptation:** To accommodate the canal's continuous bidirectional tidal fluctuations, vertical guide rails manufactured from fiber-reinforced polymer (FRP) are installed. These rails allow the bio-curtain modules to autonomously track the operational water levels, which vary from 0.74 m to 2.1 m, ensuring that the optimized 1.2 m root depth D_r is consistently maintained. Given the estuarine nature of the Dongsam tidal canal, FRP is specifically selected for its exceptional resistance to chloride-induced corrosion in high-salinity seawater. This choice enhances long-term structural integrity and minimizes maintenance requirements, effectively mitigating the rapid degradation typical of conventional metallic fixtures in marine environments.
- **Hydrodynamic Reconfiguration:** During low-tide peaks, the flexible roots deflect downstream to maintain hydraulic conveyance. Simultaneously, the increased relative density of the root matrix within the reduced water column acts as a physical 'straining sweep.' This mechanism effectively traps suspended particles through interception and localized sedimentation, thereby polishing the discharge water by reducing turbidity before it exits the canal.

5.1.6. Hybrid Synergy: Spatial Allocation and Aeration Integration

To maximize the treatment performance at localized point-source inflows (nodes D-2 and D-3), an engineered synergy between the bio-curtains and Type II aeration units is proposed through the following strategic configurations:

- **Targeted Scaling and Placement:** Instead of broad spatial coverage, the bio-curtain modules are strategically deployed in concentrated clusters immediately adjacent to the primary inflow points. This placement is designed to intercept the pollution plume at its source before

significant dispersion occurs. By utilizing a high areal planting density of 16–24 plants/m², the configuration aims to establish a robust and dense rhizosphere. This high-density setup serves as the primary zone for intensive biofilm-mediated remediation, maximizing the volumetric reactive surface area where pollutant concentrations are highest. This targeted approach ensures that the localized hydrodynamic activation provided by the aeration units is fully leveraged for enhanced nutrient removal kinetics.

- **HRT Optimization via Spiral Mixing:** A single Type II spiral aeration unit is strategically integrated immediately upstream of the bio-curtain cluster. As discussed in Section 5.1.2, the primary objective of this setup is to extend the hydraulic retention time (HRT) rather than providing bulk aeration. The upward bubble plume is intended to generate a localized, controlled spiral mixing zone that retards pure longitudinal advection. This hydrodynamic delay is anticipated to allow the polluted water to permeate the root-biofilm matrix multiple times before exiting the treatment zone, effectively increasing the contact time.
- **Enhanced Treatment Potential:** This engineered synergy is expected to maximize the contact frequency between dissolved pollutants and the bio-reactive surfaces on the plant roots. Compared to traditional linear flow interception systems, this hybrid configuration is anticipated to significantly enhance the system's nutrient sequestration and overall pollutant removal efficiency, offering a robust, proposed solution for point-source pollution control.

5.2. Preliminary Assessment of International Tidal Canals

5.2.1. Selection of Target Micro-tidal Canals and Environmental Profiles

To evaluate the global scalability of the hybrid water purification framework, its applicability was preliminarily assessed across 15 international micro-tidal canals. The selection process was strictly guided by the physical and biological operational limits established for the Dongsam tidal canal, ensuring that the comparative waterways share similar geometric and hydrodynamic profiles. While only three of the selected canals (Dotonbori, Khlong Phadung, and Rochor) utilize dual-gate operations similar to the Dongsam tidal canal, the remaining 12 canals are inherently subject to chronic stagnation due to their micro-tidal characteristics. The proposed hybrid framework, optimized for the 'zero-flow' conditions induced by gate closures, serves as a conservative 'worst-case scenario' design. Consequently, this ensures that the system provides a robust purification capacity not only during artificial gate-induced stagnation but also during natural quiescent phases common in energy-limited micro-tidal environments.

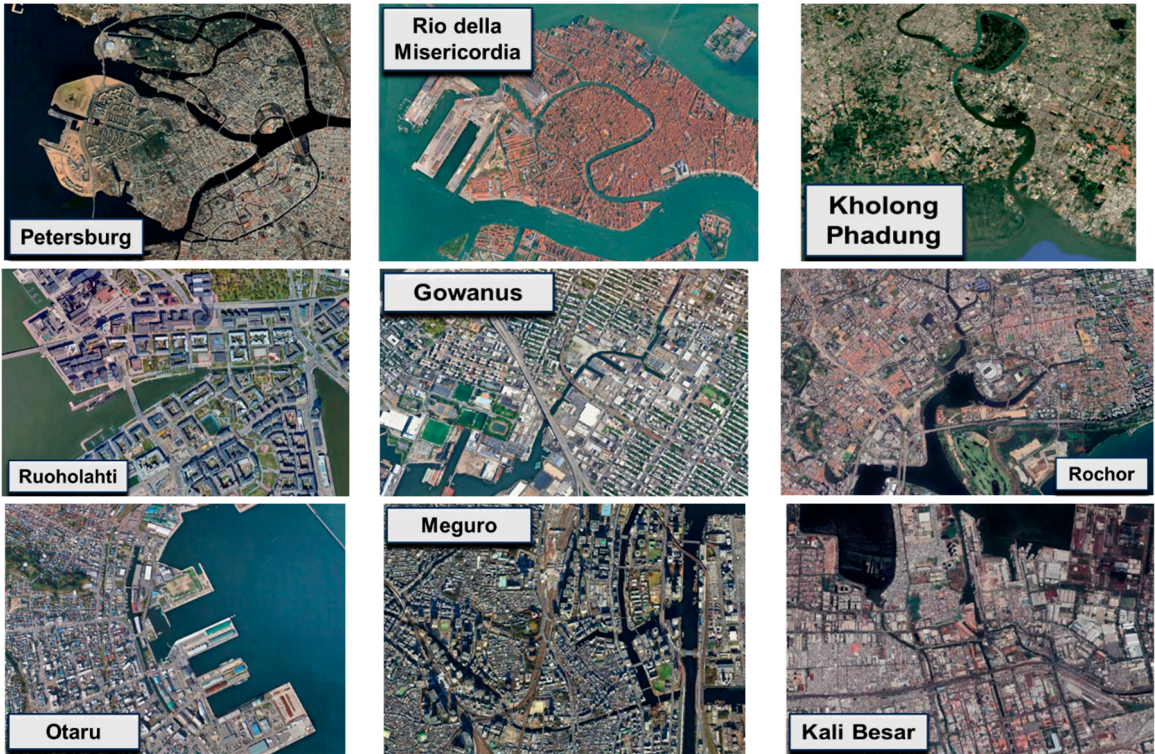
To derive a robust dataset for this feasibility assessment, the target canals were screened based on three integrated engineering criteria. Geometrically, the canals were restricted to a maximum width of ≤ 30 m; this constraint ensures that the spiral flow generated by the aeration units, when deployed in a staggered configuration as proposed in Section 4.2.2, can effectively reach the banks. This width also ensures that the vertical bio-curtains can be strategically positioned to intercept the flow as an integrated bio-curtain system without significant hydraulic bypass. Hydrodynamically, the maximum tidal range was limited to under 2.0 m to guarantee the structural stability of the wall-mounted FRP guide rails, with a preference for systems capable of dual-gate operations to mimic the quiescent tidal intervals analyzed in this study.

Environmentally, the selected sites encompass a wide spectrum of thermal regimes and urban discharge types, ranging from low-impact stormwater to severe combined sewer overflows (CSOs) and raw sewage. These conditions necessitate the creation of an "oxygen refuge" and dictate the required removal kinetics for total nitrogen (TN) and total phosphorus (TP). The environmental and geometric profiles of these 15 selected canals are systematically categorized in Table 4, with their corresponding spatial configurations across three climate zones visualized through Google Earth Pro satellite imagery in Figure 9.

Table 4. Geometric and Environmental Profiles of 15 International Micro-tidal Canals.

Climate Zone	Location (City, Country)	Annual Temp. (°C)	Length (km)	Rep. Width (m)	Depth (m)	Max. Tidal Range (m)	Urban Discharge Type (Sewage & CSOs)
Cold	Griboyedov Canal (St. Petersburg, Russia)	-15 to 25	5.0	22.5 (20–25)	2.25 (2.0–2.5)	< 0.5	Moderate (Sewer Leaks)
	Ruoholahti Canal (Helsinki, Finland)	-10 to 23	1.2	17.5 (15–20)	2.50 (2.0–3.0)	< 0.5	Low-Moderate (Stormwater)
	Otaru Canal (Otaru, Japan)	-8 to 26	1.1	25.0 (20–30)	2.00 (1.5–2.5)	< 0.5	Low-Moderate (Graywater)
	Rosenlundskanalen (Gothenburg, Sweden)	-5 to 24	1.5	20.0 (15–25)	2.25 (2.0–2.5)	0.5	Moderate (CSOs)
	Slotsholmskanalen (Copenhagen, Denmark)	-3 to 25	1.0	22.5 (20–25)	2.75 (2.5–3.0)	< 0.5	Low (Regulated Runoff)
Temperate	Rio della Misericordia (Venice, Italy)	-2 to 33	1.2	12.5 (10–15)	2.00 (1.5–2.5)	1.0	High (Domestic Sewage)
	Gowanus Canal (New York, USA)	-5 to 34	2.9	30.0 (3.0–4.0)	3.50 (3.0–4.0)	1.4	Severe (CSOs)
	Meguro River (Tokyo, Japan)	0–35	4.0	27.5 (25–30)	2.50 (2.0–3.0)	1.5	Moderate-High (CSOs)
	Dotonbori Canal (Osaka, Japan)	2–35	2.7	27.5 (25–30)	2.50 (2.0–3.0)	< 1.5*	High (Commercial Runoff)
	Hawthorne Canal (Sydney, Australia)	8–30	2.5	17.5 (15–20)	1.75 (1.5–2.0)	1.5	Moderate (Stormwater)
Tropical	Khlong Phadung (Bangkok, Thailand)	22–38	5.5	22.5 (20–25)	2.50 (2.0–3.0)	~1.5*	Severe (Untreated Runoff/ Graywater)
	Rochor Canal (Singapore)	24–34	1.5	22.5 (20–25)	2.25 (2.0–2.5)	< 0.5*	Moderate (Monsoon Runoff)
	Kali Besar (Jakarta, Indonesia)	24–35	1.2	25.0 (20–30)	2.00 (1.5–2.5)	1.0	Severe (Raw Sewage)
	Estero de Paco (Manila, Philippines)	23–35	2.9	12.5 (10–15)	1.50 (1.0–2.0)	1.0	Severe (Domestic Discharge)
	Nhieu Loc-Thi Nghe (Ho Chi Minh, Vietnam)	22–36	8.7	27.5 (25–30)	2.50 (2.0–3.0)	1.8	High (CSOs)

Note: 1) Data representing depth and tidal range are averaged approximations. 2) “” Tidal exchange regulated by barrage or lock systems. 3) CSO: combined sewer overflow.



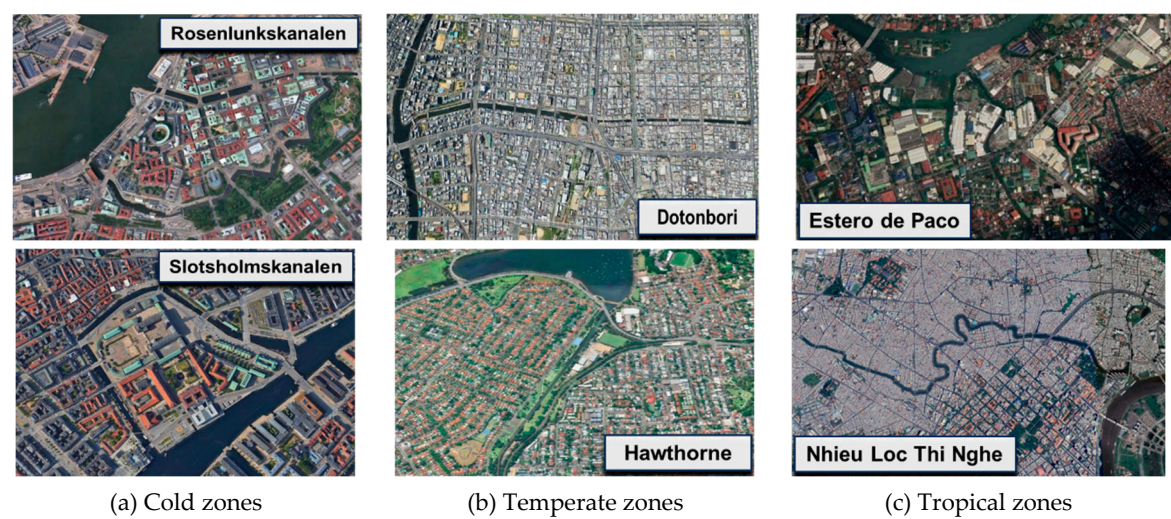


Figure 9. Satellite imagery of the 15 selected international micro-tidal canals [45].

5.2.2. Evaluation of Scaling Logic for Global Aeration Design

To demonstrate the versatility of the hybrid system, the scaling logic established in section 4 is applied to the 15 international canals, evaluating how the universal mixing parameter (W_{eff}) adapts to diverse geometric scales. The evaluation focuses on the strategic allocation of aeration intensity and node types based on the specific urban discharge profiles identified in Table 4. The design considerations for aeration system are presented in Table 5.

Table 5. Optimized Spiral Flow Aeration Design Matrix for 15 International Canals.

Climate Zone	Location (City, Country)	Layout Configuration	W_{eff} (m)	L_s (m)	Z_c (m)	L_{sb} (m)
Cold	Griboyedov Canal (St. Petersburg, Russia)	Bilateral Staggered	5.6	56	0.45	7.5
	Ruoholahti Canal (Helsinki, Finland)	Bilateral	6.3	63	0.5	7.5
	Otaru Canal (Otaru, Japan)	Bilateral Staggered	5.0	50	0.4	7.5
	Rosenlundskanalen (Gothenburg, Sweden)	Bilateral Staggered	5.6	56	0.45	7.5
	Slotsholmskanalen (Copenhagen, Denmark)	Bilateral Staggered	6.9	69	0.55	7.5
Temperate	Rio della Misericordia (Venice, Italy)	Single-sided	5.0	50	0.40	15.0
	Gowanus Canal (New York, USA)	Bilateral Staggered	8.8	88	0.70	21.0
	Meguro River (Tokyo, Japan)	Bilateral Staggered	6.3	63	0.50	22.5
	Dotonbori Canal (Osaka, Japan)	Bilateral Staggered	6.3	63	0.50	22.5
	Hawthorne Canal (Sydney, Australia)	Bilateral	4.4	44	0.35	22.5
Tropical	Khlong Phadung (Bangkok, Thailand)	Bilateral Staggered	6.3	63	0.50	22.5
	Rochor Canal (Singapore)	Bilateral Staggered	5.6	56	0.45	7.5
	Kali Besar	Bilateral Staggered	5.0	50	0.40	15.0

(Jakarta, Indonesia)						
Estero de Paco (Manila, Philippines)	Single-sided	3.8	38	0.30	15.0	
Nhieu Loc- Thi Nghe (Ho Chi Minh, Vietnam)	Bilateral Staggered	6.3	63	0.50	27.0	

- **Application of the Universal Scaling Parameter (W_{eff}):** The core of the global design logic rests on the effective mixing width, defined as $W_{eff} = 2.5h$. Across the 15 canals, where depths (h) range from 1.5 m (Estero de Paco) to 3.5 m (Gowanus Canal), the calculated W_{eff} varies between 3.75 m and 8.75 m. This adaptive parameter ensures that the spiral aeration units are not over-designed for narrow channels like the Rio della Misericordia ($W = 12.5$ m) while maintaining sufficient energy to cover the wider spans of the Meguro River or Dotonbori Canal ($W \approx 30$ m).
- **Implementation of the Intensive Mixing Zone ($4 \times W_{eff}$):** For all selected sites, the target purification reach is proposed to be constrained within the intensive mixing zone ($4 \times W_{eff}$). Based on the analysis in Section 5.1.2, this $4 \times W_{eff}$ reach—ranging from 15 m to 35 m globally—is intended to maximize the angular momentum of the spiral flow. By concentrating the bio-curtain clusters within this high-energy envelope, the system is anticipated to facilitate the most efficient contact between the polluted inflow and the nitrifying biofilms, regardless of the canal’s total longitudinal length.
- **Strategic Node Allocation by Discharge Severity:** The allocation between Type I (Refuge) and Type II (Targeted Control) nodes is proposed to scale with the “Urban discharge type” categorized in Table 4.
 - **Severe Impact Zones (e.g., Kali Besar, Nhieu Loc-Thi Nghe):** For canals receiving raw sewage or heavy CSOs, a sequential Type I relay system is proposed. By deploying units at $10 \times W_{eff}$ intervals, the design aims to establish a continuous aerobic corridor to prevent localized fish kills during quiescent tidal intervals.
 - **Moderate/Low Impact Zones (e.g., Griboyedov, Ruoholahti):** In canals primarily affected by graywater or regulated runoff, localized Type II targeted control nodes are intended to provide an efficient, low-energy solution. These nodes focus on extending the hydraulic retention time (HRT) at specific point-source inflows, potentially enhancing nutrient sequestration without the need for full-corridor aeration.
- **Performance Anticipation under ‘Worst-Case’ Stagnation:** By optimizing the system for the ‘zero-flow’ conditions typical of the Dongsam tidal canal’s gate operations, the scaling logic is expected to remain robust across the 12 canals without formal gate systems. During natural slack tides or low-velocity periods common in these micro-tidal environments, the induced spiral momentum is anticipated to act as an artificial flushing mechanism, preventing the formation of stagnant boundary layers and maintaining the dissolved oxygen (DO) above the critical hypoxia threshold.

5.2.3. Evaluation of Scaling Logic for Global Bio-curtain and Anchoring Design

The strategic deployment of vertical bio-curtains across the 15 international canals is summarized in Table 6. The scaling logic for these systems integrates biological adaptation with structural resilience, ensuring the modules remain functional under diverse chemical and hydrodynamic stresses.

Table 6. Optimized Bio-curtain and Adaptive Anchoring Design Matrix.

Climate Zone	Location (City, Country)	Representative Species	Root depth (D_r) (m)	Density (ρ_p) (plants/m ²)	Adaptive anchoring (Guide rail)
Cold	Griboyedov Canal (St. Petersburg, Russia)	Phragmites australis & Typha latifolia	1.35	12-16	FRP (Ice & Salt resilience)
	Ruoholahti Canal (Helsinki, Finland)		1.50		Corrosion-resistant poly-coated
	Otaru Canal (Otaru, Japan)		1.20		FRP (Winter salt tolerance)
	Rosenlundskanalen (Gothenburg, Sweden)		1.35		Reinforced FRP (CSO durability)
	Slotsholmskanalen (Copenhagen, Denmark)		1.65		Standard durable synthetic
Temperate	Rio della Misericordia (Venice, Italy)	Iris pseudacorus	1.20	16-24	FRP (High salinity & sewage)
	Gowanus Canal (New York, USA)		2.10		FRP (Severe CSO resilience)
	Meguro River (Tokyo, Japan)		1.50		FRP (Aesthetic & durable)
	Dotonbori Canal (Osaka, Japan)		1.50		FRP (Commercial runoff protection)
	Hawthorne Canal (Sydney, Australia)		1.05		FRP (Estuarine marine grade)
Tropical	Khlong Phadung (Bangkok, Thailand)	Canna indica & Cyperus papyrus	1.50	24-32	FRP (High chemical resistance)
	Rochor Canal (Singapore)		1.35		FRP (UV & monsoon stability)
	Kali Besar (Jakarta, Indonesia)		1.20		FRP (Severe organic load)
	Estero de Paco (Manila, Philippines)		0.90		FRP (Informal settlement discharge)
	Nhieu Loc-Thi Nghe (Ho Chi Minh, Vietnam)		1.50		FRP (High microbial load)

- **Biological Scaling and Density Gradient:** To maximize nutrient sequestration potential, the planting density (ρ_p) is systematically scaled according to the thermal regimes and metabolic expectations defined in Chapter 4.
 - **Cold Zones (12–16 plants/m²):** A conservative density is applied to maintain essential hydrodynamic porosity, preventing root overcrowding and anaerobic rot during prolonged winter dormant phases. A polyculture strategy (*Phragmites* and *Typha*) is utilized to enhance winter resilience.
 - **Temperate Zones (16–24 plants/m²):** A median optimization approach is proposed as an optimal baseline. Utilizing monoculture (*Iris pseudacorus*), this range ensures rapid canopy closure and maximizes nutrient assimilation during the growing season while preventing localized root-zone hypoxia.

- **Tropical Zones (24–32 plants/m²):** An ultra-high-density approach is employed to capitalize on year-round rapid biomass growth and elevated microbial kinetics. The polyculture of *Canna* and *Cyperus* fully maximizes the surface-area-to-volume (SA/V) ratio to effectively manage the massive organic loads typical of these environments.
- **Adaptive Anchoring and Operational Resilience:** The implementation of a robust vertical support system is the primary requirement for ensuring the physical stability and functional positioning of modular bio-curtains. For the 15 international canals, fiber-reinforced polymer (FRP) is proposed as the primary material for the vertical guide rails. FRP pultruded profiles exhibit superior chemical resilience against sulfides and organic acids common in untreated urban discharges—a strategic choice for cities like Bangkok, Manila, and Ho Chi Minh City, where microbial and chemical loads are substantial.
- **Autonomous Water Level Tracking and Root Depth (D_r) Optimization:** The FRP guide rail system allows the bio-curtain modules to autonomously track tidal fluctuations. This ensures that the root-biofilm matrix remains at the optimized immersion ratio ($D_r/h = 0.6$) regardless of the tidal phase. This autonomous adjustment maintains consistent interception of pollutant plumes from outfalls, preventing hydraulic bypass during high-tide events.
- **Landscape and Social Value:** Beyond structural durability, these anchored systems are strategically positioned to provide a visual masking effect. By concealing unsightly infrastructure, such as exposed sewage pipes or stormwater conduits in high-traffic promenades like Tokyo's Meguro river or Osaka's Dotonbori canal, the nature-based integration enhances public perception and the recreational experience for waterfront visitors.

6. Conclusions

6.1. Summary

This study originated from empirical field observations and water quality analyses of the 2022 mass fish mortality event at the Dongsam tidal canal. In-situ monitoring quantitatively revealed that during the 'Tidal window gap'—a period of hydraulic stagnation required to build hydraulic head for tidal flushing—bottom-layer dissolved oxygen (DO) rapidly plummeted to a critical anoxic state of 0.44 mg/L. Furthermore, laboratory analyses of urban discharge points identified high concentrations of organic matter (COD) and nutrients (TN, TP) as the primary catalysts for hypoxia. These findings confirm that passive tidal exchange systems possess fundamental limitations in preventing acute ecological disasters during stagnant intervals.

To address these constraints, this study proposed a hybrid water purification framework integrating active ecological interventions. This system synergizes wall-mounted spiral flow aeration for continuous oxygenation with vertical bio-curtains for point-source pollutant interception. Core engineering parameters were systematically derived: the effective mixing width ($W_{eff} \approx 2.5h$) and longitudinal spacing ($L_s = 10 \times W_{eff}$) to maximize aeration efficiency, and an optimized root immersion ratio ($D_r/h = 0.6$) paired with climate-adaptive planting densities to maximize the surface area-to-volume (SA/V) ratio. The implementation of a corrosion-resistant FRP guide rail system was proposed to facilitate autonomous adaptation to tidal fluctuations.

The practical viability of this framework was first conceptualized through a prototype design for the Dongsam tidal canal—leveraging its site-specific geometric and environmental data—and was subsequently extended to 15 international micro-tidal canals across diverse climatic zones. By scaling the aeration layouts and vegetation matrices according to site-specific profiles, this research details the essential engineering considerations required for global implementation. Rather than asserting immediate empirical validation, this systematic assessment presents a comprehensive methodology and a flexible engineering toolkit intended to guide future resilient water quality management in shallow urban waterways worldwide.

6.2. Limitations and Recommendations

While this research establishes a rigorous methodological framework and standardized design considerations; it is subject to certain academic limitations that define the scope for future investigations. Primarily, as the study focuses on a theoretically grounded engineering methodology, it lacks longitudinal field-scale data to empirically verify real-time purification performance—such as specific DO recovery rates and nutrient reduction—across the 15 selected international canals. Furthermore, the current scaling logic assumes optimized ecological conditions for vegetation and microbial metabolism, which may not fully account for the complex, stochastic variables of urban environments, such as acute toxic chemical influxes or extreme meteorological events.

To address these constraints and enhance the practical reliability of the hybrid system, several recommendations are proposed. First, long-term field monitoring at representative testbeds, such as the Dongsam tidal canal, is essential to calibrate core design parameters—including the effective mixing width (W_{eff}), longitudinal spacing (L_s), and setback distances (L_{sb}). Second, future work should employ advanced 3D numerical modeling to simulate the integrated mechanisms of spiral-flow-induced oxygen transfer and rhizosphere-mediated pollutant sequestration. Finally, the structural stability and bio-fouling resistance of the FRP guide rail system must be evaluated under diverse tidal and flow conditions to ensure long-term operational resilience and to optimize maintenance protocols.

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Abbreviations

The following abbreviations are used in this manuscript:

COD	Chemical Oxygen Demand
CSO	Combined Sewer Overflow
DO	Dissolved Oxygen
FTW	Floating Treatment Wetland
FRP	Fiber Reinforced Polymer
HRT	Hydraulic Retention Time
KHOA	Korea Hydrographic and Oceanographic Agency
KMOU	Korea Maritime & Ocean University
NbS	Nature-based Solution
O&M	Operations and Maintenance
OTE	Oxygen Transfer Efficiency
SA/V	Surface Area-to-Volume

SOD	Sediment Oxygen Demand
TN	Total Nitrogen
TP	Total Phosphorus
ZAI	Zone of Aeration Influence

References

1. Monsen, N.E.; Cloern, J.E.; Lucas, L.V.; Monismith, S.G. A comment on the use of flushing time, residence time, and age as transport time scales. *Limnol. Oceanogr.* **2002**, *47*, 1545–1553. <https://doi.org/10.4319/lo.2002.47.5.1545>
2. Johnston, S.G.; Slavich, P.G.; Hirst, P. The impact of controlled seawater exchange on water quality in acid sulfate soil environments. *Agric. Water Manage.* **2005**, *73*, 87–112. <https://doi.org/10.1016/j.agwat.2004.10.005>
3. Jin, S.; Kim, D.; Lim, H.S.; Lee, H.J. Variability of flow velocity induced by Dongsam Seawater Stream Floodgate installation. *J. Coast. Disaster Prev.* **2021**, *8(4)*, 267–274. <https://doi.org/10.20481/kscdp.2021.8.4.267>
4. Hong, S.; Jin, S.; Kim, K.T.; Kim, D.; Kim, J.; Jang, S.C.; Kim, H.; Park, J.H.; Lim, H.S. The effects of increasing flow velocity and improving water quality in Dongsam seawater stream through bi-directional sluice gates operation and tidal range drainage. *J. Coast. Disaster Prev.* **2023**, *10(3)*, 95–109. <https://doi.org/10.20481/kscdp.2023.10.3.95>
5. ASCE/EWRI. *Measurement of Oxygen Transfer in Clean Water*, ASCE/EWRI 2-06; American Society of Civil Engineers: Reston, VA, USA, **2007**.
6. U.S. Environmental Protection Agency (EPA). *Combined Sewer Overflow O&M Fact Sheet*; EPA 832-F-99-039; Office of Water: Washington, DC, USA, **1999**.
7. Korea Hydrographic and Oceanographic Agency (KHOA). *Tide Tables for Coast of Korea*; KHOA: Busan, Republic of Korea, **2022**.
8. Chow, V.T. *Open-Channel Hydraulics*; McGraw-Hill: New York, NY, USA, **1959**.
9. Henderson, F.M. *Open Channel Flow*; Macmillan: New York, NY, USA, **1966**.
10. Diaz, R.J.; Rosenberg, R. Spreading dead zones and consequences for marine ecosystems. *Science* **2008**, *321*, 926–929. <https://doi.org/10.1126/science.1156401>
11. Vaquer-Sunyer, R.; Duarte, C.M. Thresholds of hypoxia for marine biodiversity. *Proc. Natl. Acad. Sci. USA* **2008**, *105(40)*, 15452–15457. <https://doi.org/10.1073/pnas.0803833105>
12. Tchobanoglous, G.; Stensel, H.D.; Tsuchihashi, R.; Burton, F.L. *Wastewater Engineering: Treatment and Resource Recovery*, 5th ed.; McGraw-Hill Education: New York, NY, USA, **2014**.
13. Fayolle, Y.; Cockx, A.; Gillot S.; Roustan, M.; Héduit, Alain. Oxygen transfer prediction in aeration tanks using CFD. *Chem. Eng. Sci.* **2007**, *62(24)*, 7163–7171. <https://doi.org/10.1016/j.ces.2007.08.082>
14. Chanson, H. *The Hydraulics of Open Channel Flow: An Introduction*, 2nd ed.; Butterworth-Heinemann: Oxford, UK, **2004**.
15. Eby, L.A.; Crowder, L.B. Hypoxia-based habitat compression in the Neuse River Estuary: context-dependent shifts in behavioral avoidance thresholds. *Can. J. Fish. Aquat. Sci.* **2002**, *59(6)*, 952–965. <https://doi.org/10.1139/f02-067>
16. Alp, E.; Melching, C.S. Allocation of supplementary aeration stations in the Chicago waterway system for dissolved oxygen improvement. *J. Environ. Manage.* **2011**, *92(6)*, 1577–1583. <https://doi.org/10.1016/j.jenvman.2011.01.014>
17. Novak, P.; Moffat, A.I.B.; Nalluri, C.; Narayanan, R. *Hydraulic Structures*, 4th ed.; Spon Press: London, UK, **2001**.
18. Unger, J.; Hager, W.H. Down-flow and horseshoe vortex characteristics of sediment embedded bridge piers. *Exp. Fluids* **2007**, *42*, 1–19. <https://doi.org/10.1007/s00348-006-0209-7>
19. Ashton, G.D. *River and Lake Ice Engineering*; Water Resources Publications: Littleton, CO, USA, **1986**.
20. Fischer, H.B.; List, E.J.; Koh, R.C.Y.; Imberger, J.; Brooks, N.H. *Mixing in Inland and Coastal Waters*; Academic Press: New York, NY, USA, **1979**.
21. Borne K.E.; Fassman-Beck, E.A.; Winston, R.J.; Hunt, W.F.; Tanner C.C. Implementation and Maintenance of Floating Treatment Wetlands for Urban Stormwater Management. *J. Environ. Eng.* **2015**, *141(11)*, 04015017. [https://doi.org/10.1061/\(ASCE\)EE.1943-7870.0000959](https://doi.org/10.1061/(ASCE)EE.1943-7870.0000959)

22. Vymazal, J. Removal of nutrients in various types of constructed wetlands. *Sci. Total Environ.* **2007**, *380*, 48–65. <https://doi.org/10.1016/j.scitotenv.2006.09.014>
23. Kadlec, R.H.; Wallace, S. *Treatment Wetlands*, 2nd ed.; CRC Press: Boca Raton, FL, USA, **2008**.
24. Li, X.N.; Song, H.L.; Li, W.; Lu, X.W.; Nishimura, O. An integrated ecological floating-bed employing plant, freshwater clam and biofilm carrier for purification of eutrophic water. *Ecol. Eng.* **2010**, *36*(4), 382–390. <https://doi.org/10.1016/j.ecoleng.2009.11.004>
25. Colares, G.S.; Dell’Osbel, N.; Wiesel, P.G.; Oliveira, G.A.; Lemos, P.H.Z.; da Silva, F.P.; Lutterbeck, C.A.; Kist, L.T.; Machado, Ê.L. Floating treatment wetlands: A review and bibliometric analysis. *Sci. Total Environ.* **2020**, *714*, 136776. <https://doi.org/10.1016/j.scitotenv.2020.136776>
26. Borne, K.E. Floating treatment wetlands: influences on the fate and removal performance of phosphorus in stormwater retention ponds. *Ecol. Eng.* **2014**, *69*, 76–82. <https://doi.org/10.1016/j.ecoleng.2014.03.062>
27. Headley, T.R.; Tanner, C.C. Constructed wetlands with floating emergent macrophytes: an innovative stormwater treatment technology. *Crit. Rev. Environ. Sci. Technol.* **2012**, *42*, 2261–2310. <https://doi.org/10.1080/10643389.2011.574108>
28. Haslam, S.M. Biological flora of the British Isles: *Phragmites communis* Trin. *J. Ecol.* **1972**, *60*(2), 585–610. <https://doi.org/10.2307/2258363>
29. Grace, J.B.; Harrison, J.S. The biology of Canadian weeds. 73. *Typha latifolia* L., *Typha angustifolia* L. and *Typha xglauca* Godr. *Can. J. Plant Sci.* **1986**, *66*, 361–379. <https://doi.org/10.4141/cjps86-051>
30. Vymazal, J. Plants used in constructed wetlands with horizontal subsurface flow: a review. *Hydrobiologia* **2011**, *674*, 133–156. <https://doi.org/10.1007/s10750-011-0738-9>
31. Kaseva, M.E. Performance of a sub-surface flow constructed wetland in polishing pre-treated wastewater – a tropical case study. *Water Res.* **2004**, *38*(3), 681–687. <https://doi.org/10.1016/j.watres.2003.10.041>
32. Sutherland, W.J. Biological flora of the British Isles: *Iris pseudacorus* L. *J. Ecol.* **1990**, *78*, 833–848. <https://doi.org/10.2307/2260902>
33. Wu, S.; Kuschik, P.; Brix, H.; Vymazal, J.; Dong, R. Development of constructed wetlands in performance intensifications for wastewater treatment: A nitrogen and organic matter targeted review. *Water Res.* **2014**, *57*, 40–55. <https://doi.org/10.1016/j.watres.2014.03.020>
34. Konnerup, D.; Koottatep, T.; Brix, H. Treatment of domestic wastewater in tropical, subsurface flow constructed wetlands planted with *Canna* and *Heliconia*. *Ecol. Eng.* **2009**, *35*(2), 248–257. <https://doi.org/10.1016/j.ecoleng.2008.04.018>
35. Muthuri, F.M.; Jones, M.B.; Imbamba, S.K. Papyrus: Primary productivity of papyrus (*Cyperus papyrus*) in a tropical swamp; Lake Naivasha, Kenya. *Biomass.* **1989**, *18*(1), 1–14. [https://doi.org/10.1016/0144-4565\(89\)90077-2](https://doi.org/10.1016/0144-4565(89)90077-2)
36. Kyambadde, J.; Kansime, F.; Gumaelius, L.; Dalhammar, G. A comparative study of *Cyperus papyrus* and *Miscanthidium violaceum*-based constructed wetlands for wastewater treatment in a tropical climate. *Water Res.* **2004**, *38*(2), 475–485. <https://doi.org/10.1016/j.watres.2003.10.008>Get rights and content
37. Tanner, C.C.; Headley, T.R. Components of floating emergent macrophyte treatment wetlands influencing removal of stormwater pollutants. *Ecol. Eng.* **2011**, *37*, 474–486. <https://doi.org/10.1016/j.ecoleng.2010.12.012>
38. Winston, R.J.; Hunt, W.F.; Kennedy, S.G.; Merriman, L.S.; Chandler, J.; Brown, D. Evaluation of floating treatment wetlands as retrofits to existing stormwater retention ponds. *Ecol. Eng.* **2013**, *54*, 254–265. <https://doi.org/10.1016/j.ecoleng.2013.01.023>
39. Pavlineri, N.; Skoulikidis, P.T.; Tsihrintzis, V.A. Constructed floating wetlands: A review of research, design, operation and management aspects, and data meta-analysis. *Chem. Eng. J.* **2017**, *308*, 1120–1132. <https://doi.org/10.1016/j.cej.2016.09.140>
40. Francis, R.A.; Hoggart, S.P.G. Waste not, want not: The need to utilize existing artificial structures for habitat improvement along urban rivers. *Restor. Ecol.* **2008**, *16*, 372–382. <https://doi.org/10.1111/j.1526-100X.2008.00434.x>
41. Hollaway, L.C. A review of the present and future utilisation of FRP composites in the civil infrastructure. *Constr. Build. Mater.* **2010**, *24*, 2428–2445. <https://doi.org/10.1016/j.conbuildmat.2010.04.062>

42. Karbhari, V.M.; Chin, J.W.; Hunston, D.; Benmokrane, B.; Juska, T.; Morgan, R.; Lesko, J.J.; Sorathia, U.; Reynaud, D. Durability gap analysis for fiber-reinforced polymer composites in civil infrastructure. *J. Compos. Constr.* **2003**, *7*, 238–247. [https://doi.org/10.1061/\(ASCE\)1090-0268\(2003\)7:3\(238\)](https://doi.org/10.1061/(ASCE)1090-0268(2003)7:3(238))
43. Sen, R.; Mullins, G. Application of FRP composites for underwater piles repair. *Compos. Part B Eng.* **2007**, *38*, 751–758. <https://doi.org/10.1016/j.compositesb.2006.07.011>
44. Breitburg, D. Effects of hypoxia, and the balance between hypoxia and enrichment, on coastal fishes and fisheries. *Estuaries* **2002**, *25*, 767–781. <https://doi.org/10.1007/BF02804904>
45. Google Earth Pro. Version 7.3.6; Google LLC: Mountain View, CA, USA, **2026**. Available online: <https://www.google.com/earth/> (accessed on 21 February 2026).

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