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Stream Water Quality Control and Odor Reduction through a Multistage Vortex Aerator: A Novel In Situ Remediation Technology

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Abstract: In this work, we report the restoration of a polluted urban stream by employing the multistage vortex aerator (MVA), an in-line mixer device that improves the dissolved oxygen concentration of polluted streams and accelerates the water purification rate. It was observed during the field experiment that the dissolved oxygen was enhanced up to 7.05 mg/L and the water quality was improved to a good grade. As a result, the complex odor was successfully eliminated and reduced by up to 71.9%, while the water quality grade was also improved by more than two grades on average. Stream water quality indicators monitored for twelve months revealed high removal rates of total phosphorous (56.4%) and suspended solids (61%). The study demonstrated MVA as a promising eco-friendly technology for significant improvement in urban stream water quality. Moreover, the MVA process creates no secondary pollution and is believed to be a sustainable treatment option for odorous water bodies. Overall, the MVA process is technically feasible for implementation, and this study provides a specific reference as a basis for the treatment of polluted water bodies in urban settings.

Keywords: multistage vortex aerator; dissolved oxygen; odor reduction; water quality control

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1. Introduction

Water is not only necessary for all life on Earth, but it is also a valuable resource for human civilization [1]. Urban growth and transitional development have worsened the environment as industry and urbanization have accelerated rapidly. Large amounts of industrially polluted wastewater and domestic sewage are discharged arbitrarily during urban construction and development [2]. Excessive discharge significantly reduces the self-purification capacity of river water bodies and contributes to eutrophication issues in lakes and rivers. Contaminated odorous water bodies generate substantial environmental concerns around the globe today, threatening ecological integrity, compromising the image of the metropolitan landscape, and increasing people's health risk index [3]. Odorous water bodies develop due to dynamic water factors, metal element pollution, organic pollution, sediment pollution, and other variables [4]. The problem is primarily caused by a combination of physical (such as temperature), chemical (such as FeS and/or MnS in enveloping water formed by the interaction of Fe^{2+} or Mn^{2+} with S^{2-}), and biological (such as algae) reactions of pollutants in the water under hypoxic or anaerobic conditions [5–7]. Rivers and lakes in cities and towns serve several purposes, including water supply, temperature regulation, and water storage [8]. They play an essential role in ensuring the stability of the human ecological environment. Therefore, treating odorous water bodies in today's urban water environment is of utmost importance.

Treatment approaches for odorous water bodies are classified into four categories: physical, chemical, biological, and ecological restoration technologies [9]. The physical, chemical, and biological treatment measures are in situ treatment methods, while restoration is an ex situ treatment technique. Some examples of standard physical treatment technologies include pollution interception and source management, sediment dredging, aeration, and oxygenation [10,11]. Physical methods, in general, may remove pollutants from water bodies without generating secondary pollution, but the expense is often high, and the workload is significant.

On the other hand, chemical treatment methods include flocculation and sedimentation, algae-removing agents, adsorbents, and so forth [12]. Chemical treatment processes have immediate effects and are highly relevant; nevertheless, an excessive chemical injection results in serious secondary contamination [6]. Biological methods, in principle, are natural and environmentally benign, with high stability, although they require a more extended treatment cycle. Biofilm technology and aquatic plant purification are two examples of biological treatments [13]. These techniques, however, are prone to secondary pollution and are not appropriate for the continuous and effective purification of water under complex conditions. Ex situ treatment by restoration entails separating and transferring the polluted water and sediments to water treatment facilities and returning the treated water to the initial water body. However, external treatment and restoration technology demand a sizable investment of material and monetary resources. Dealing with the extracted sediment from the water body presents another challenging issue [14]. In this context, pure oxygen injection employing a multistage vortex aerator (MVA) can be a promising in situ treatment alternative to alleviate the possibility of secondary pollution. Additionally, there are no reports on stream water quality improvement employing an MVA system.

An adequate amount of oxygen is critical in both streams and sewers. In the absence of oxygen, volatile fatty acids and hydrogen sulfide are produced, resulting in an undesirable odor [15,16]. Hydrogen sulfide, produced by sustained anoxic conditions has a highly unpleasant odor and can be fatal in high concentrations. It has been proposed that such high concentrations of hydrogen sulfide can be reduced and controlled by employing oxygen injection [17]. Odor measurement in Korea is based on designated odor substances and complex odors. It is evaluated using the results of measurement at the boundary line and the emission limit value specified in the Odor Prevention Act. Among the 22 designated odor substances, hydrogen sulfide is the representative odor material, has a high odor index, occurs in anaerobic or anoxic conditions, and is also generated by sulfur-reducing bacteria, representative microorganisms that reduce sulfate ions to hydrogen sulfide.

Pollutants from non-point sources and sewage sludge are partially flowing and deposited into the Goejeongcheon stream, the target site of our research. Because of this, the stream's dissolved oxygen levels were near to those of anaerobic conditions. In this study, the dissolved oxygen concentration was augmented by dissolving oxygen in the target stream using the multistage vortex aerator (MVA). We evaluated the feasibility of using pure oxygen and a vortex aerator for stream restoration to suppress river anaerobicization and promote aerobic conditions. The study investigated MVA as an eco-friendly technology for the improvement of urban stream water quality parameters in a sustainable way.

2. Materials and Research Methods

2.1. Research Site Location

Goejeongcheon stream, located in Saha-gu, Busan, is a local stream. The stream flows through the downtown area and connects to the Nakdong-gang estuary. The length of the open area is 0.634 km, and the length of the concrete-covered area is 4.735 km, with a total length of 5.37 km. The stream was covered to alleviate traffic congestion, and the covered section is now used as a road. The covered stream runs through the downtown area, where residential areas and markets are closely located. Considering the land use status of the Goejeongcheon watershed, the forest area is the largest portion, covering 4.78 km^2 of the total area of 5.36 km^2, followed by residential areas and roads. Because Goejeongcheon is a low-tide river, the water level fluctuates significantly over time. As a result, when the water level is low, the bottom of the river becomes visible. According to the annual meteorological report of the Busan Meteorological Administration, the annual rain is 1495.60 mm, the lowest temperature is −12.6 °C, the highest temperature is 36.7 °C, the average yearly temperature is 14.5 °C, and the average annual humidity is 65.4%. The target site of this study is the open section of Goejeongcheon stream (Figure 1), with a total length of 0.634 km and an area of 8200 m^2. The stream connects to the estuary of the Nakdonggang river, which has the characteristics of a tidal river. The average water level is at least 31 cm, and the maximum is 127 cm. Since 2005, residents have complained about Goejeongcheon's stench, citing headaches and disruption to their living environment due to the foul odor.

Figure 1. Location of Goejeongcheon research site.

2.2. Multistage Vortex Aerator (MVA)

The multistage vortex aerator (Figure 2) is an oxygen-dissolving system that uses an in-line mixing method. This device effectively and quickly transfers the oxygen required in processes such as livestock wastewater treatment and allied fields. It was developed to accelerate wastewater purification by boosting the dissolved oxygen concentration in the wastewater and activating aerobic bacteria, as well as to reduce the occurrence of odors by decomposing various organic compounds. The multistage vortex aerator (MVA) system comprises a pure oxygen generator and an oxygen dissolver. A submerged pump transports water into the MVA, injects oxygen into the inlet, and delivers efficient mixing of oxygen and liquid via a vortex flow inside the dissolver's multistage partition walls. The absorption of gas depends on the film thickness between the gas and liquid, and the absorption rate can be increased by factors that can reduce this thickness [18]. By increasing the time and number of collisions between the two phases, the thickness of the film between the gas and liquid is decreased, and the efficiency of dissolving oxygen in the liquid increases. The detailed structure of the device is illustrated in our earlier reported work [19]. Since the MVA circulates and supplies pure oxygen, it was confirmed that the MVA increases dissolved oxygen concentrations to higher levels in a shorter time than other existing aeration devices, such as fine pore diffusers. Fine pore diffusers suffer from the drawbacks of inorganic scaling and biological fouling, which can reduce the transfer efficiency and cause excessive head loss [20].

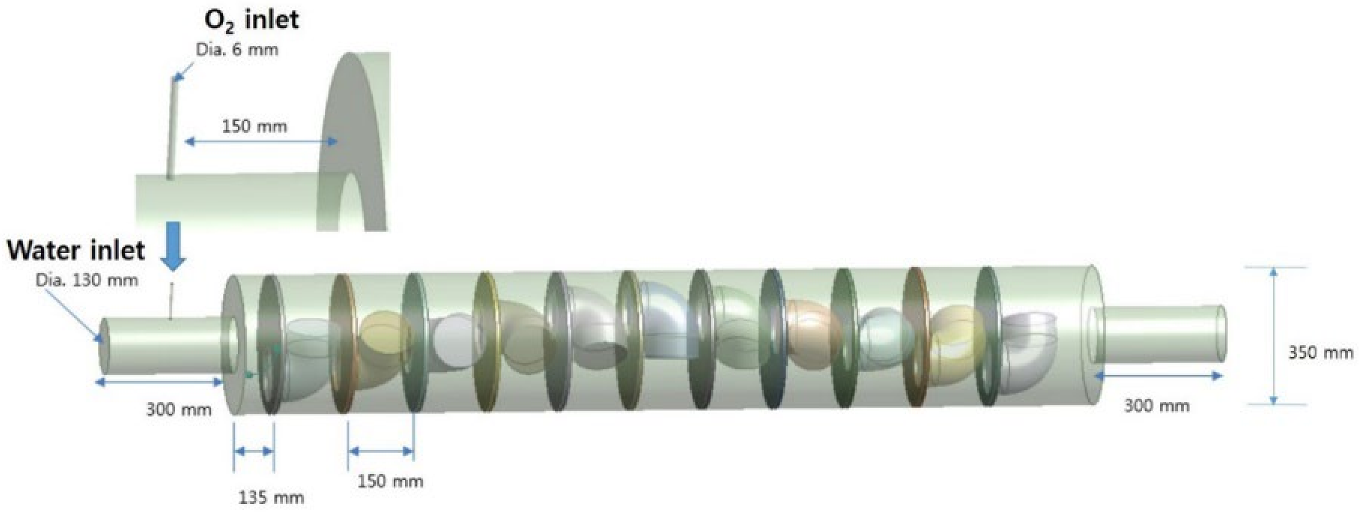

Figure 2. Pictorial representation of a multistage vortex aerator. Adapted with permission from [19].

In addition, although the conventionally used oxygenators use the 21% of oxygen in the air as an oxygen source, there is a limit to the movement speed of oxygen, whereas the multistage vortex aerator uses high-purity oxygen (about 90% oxygen). Therefore, the oxygen saturation concentration of the aqueous solution is about four times higher than that of the air diffuser, and it is observed that the dissolved oxygen in water can be rapidly increased. The increased number of collisions inside the MVA reduces the gas–liquid interfacial film thickness, thereby improving oxygen transfer efficiency.

By maintaining high dissolved oxygen (DO) levels in the river using the MVA, the aerobic microorganisms in the river can actively degrade organic debris, and high DO concentration inhibits the growth of odor-causing strictly anaerobic SRB (sulfate-reducing bacteria) [21]. The multistage vortex aerator suppresses the occurrence of anaerobic conditions, which are considered the origin of odors, enabling it to remove and prevent odors in a short period of time.

2.3. Field Experiment

The basic operation of the MVA system is depicted in Figure 3. Briefly, the river water was pumped up at a flow rate of 1 m^3/min using a submersible pump, and oxygen (~90% pure oxygen) generated through an oxygen generator was injected and dissolved into the MVA inlet. Thereafter, the oxygen-enriched water was discharged into the river. The dissolved oxygen concentration at the MVA outlet was maintained at an average of 22 mg/L. The dissolved oxygen concentration of the oxygenated water was measured by sampling through a sample collection valve located at the outlet of the MVA. The cycle was repeated for 16 h a day, and the system was operated for 12 months. The hydraulic retention time (HRT) of the water inside the MVA is 1.4 min. The oxygen generator was installed 115 m from the main public access, which is an upstream point, and the MVA outlet was installed at 90 m (point A) (Figure 4). The multistage vortex aerator consists of one oxygen generator, one dissolver, one pump, and a water level sensor.

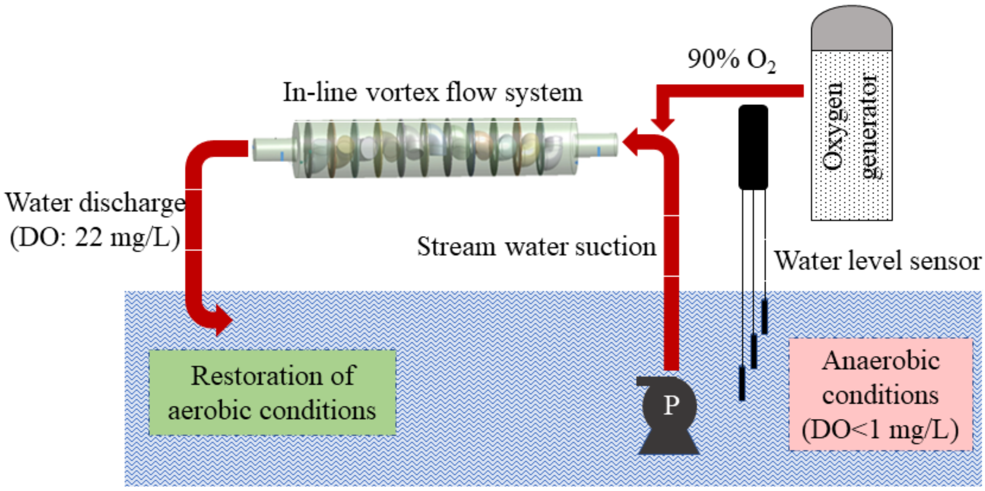

Figure 3. Schematic diagram of stream water treatment using multistage vortex aerator (MVA).

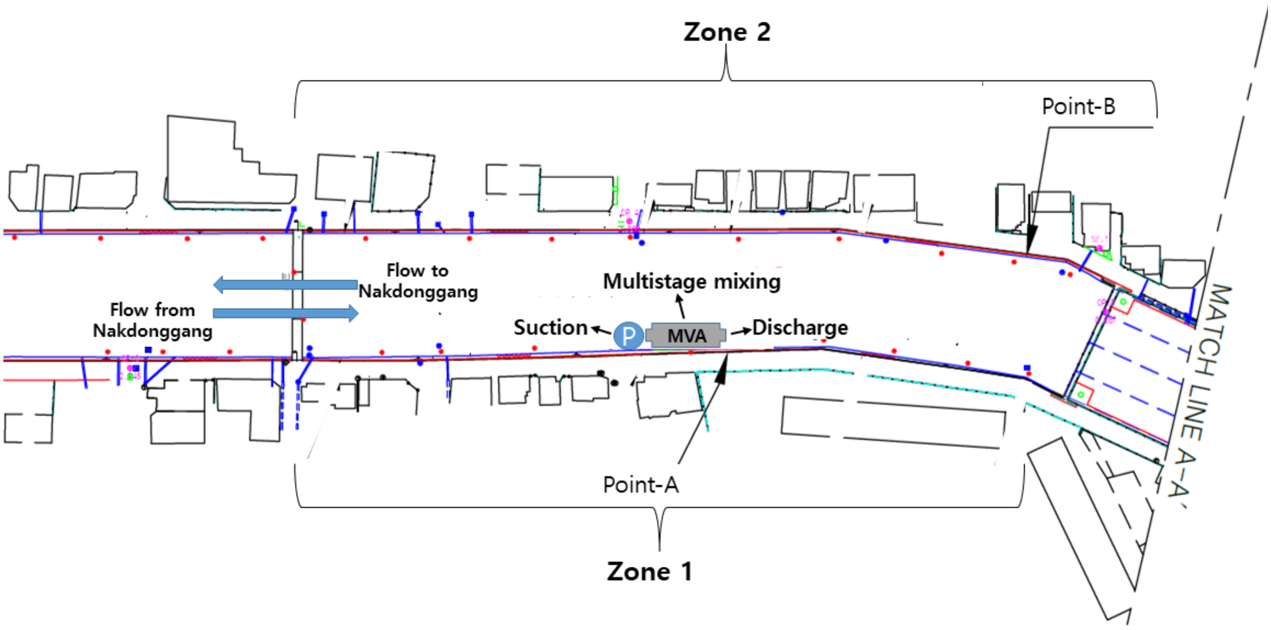

Figure 4. Schematic diagram for field experimental sampling points for water quality and odor analysis (Blue arrows illustrate the direction of water flow, and the squares represent the residential buildings).

A mechanical water level sensor was installed to enable steady system operation and prevent idling, such that the system only operated whenever the river's water level was 35 cm or higher. The mechanical water level sensor consists of three distinct sensors, each with a different length. If two or more of the three sensors are exposed to the atmosphere, the device shuts down. Furthermore, due to the device's noise, it was operated from 6 a.m. to 10 p.m.

2.4. Odor and Water Quality Analysis

2.4.1. Odor Analysis

The complex odor strength level was measured using a handheld odor meter, OMX-SRM (Shinyei, Japan). In addition, the intensity of the odor of the water samples was measured using the threshold odor number (TON) based on the olfactometric evaluation method. In this method, the sample is diluted with odor-free water until the least discernible odor is obtained.

2.4.2. Water Quality Measurement

A multi-parameter water quality meter from YSI was used to measure dissolved oxygen. The dissolved oxygen was determined by directly inserting the probe into the stream water. The measurement of suspended substances was based on the standard water quality test method, and the chemical oxygen demand (COD), total nitrogen (T-N), and total phosphorus (T-P) were performed according to the HUMAS water quality analysis KIT manual and placed into the water quality analyzer for subsequent analysis. The water quality analyzer used was the HS-2300 PLUS model, which performs measurements by the absorbance method using a color reagent.

3. Experimental Results and Discussion

3.1. Field Experiment

At the field-testing location, point A represents the section of the stream influenced by the MVA, while point B represents the section without the MVA installation (Figure 4). The section with the MVA installation is called 'zone 1', and 'zone 2′ represents the control section without the MVA installation. Goejeongcheon has the characteristics of both a lake and a river. Notably, the Water Resources Management Information System (WAMIS) standards in Korea are more stringent for lake water quality, and therefore, we adopted these criteria for our work. The effectiveness of the MVA installation was confirmed by comparing the obtained water quality data with the lake water quality and environmental standards according to WAMIS (Table 1) [22].

Table 1. Water quality parameters and environmental standards for classification.

Classification	Parameters				
	COD (mg/L)	Suspended Solids (mg/L)	Dissolved Oxygen (mg/L)	Total Phosphorous (mg/L)	Total Nitrogen (mg/L)
Very good (Ia)	2 or less	1 or less	7.5 or more	0.01 or less	0.2 or less
Good (Ib)	3 or less	5 or less	5.0 or more	0.02 or less	0.3 or less
Slightly good (II)	4 or less	5 or less	5.0 or more	0.03 or less	0.4 or less
Fair (III)	5 or less	15 or less	5.0 or more	0.05 or less	0.6 or less
Slightly bad (IV)	8 or less	15 or less	2.0 or more	0.10 or less	1.0 or less
Poor (V)	10 or less	Floating suspended matter	2.0 or more	0.15 or less	1.5 or less
Very bad (VI)	>10	_	<2.0	>0.15	>1.5

3.1.1. Dissolved Oxygen (DO)

Data for dissolved oxygen by season were recorded for one year, with the average of the data from spring to autumn being reported (Figure 5). Data analysis for each season was required to examine the effectiveness of the MVA in dissolved oxygen improvement. In Figure 5, it can be observed that the seasonal variation in dissolved oxygen concentration followed a similar pattern at points A and B, respectively. At point B, the average dissolved oxygen was 0.98 mg/L in summer, 2.55 mg/L in spring, and 1.81 mg/L in autumn, wherein spring and autumn exhibited higher dissolved oxygen concentrations compared with summer because the dissolved oxygen concentration is inversely correlated to the stream temperature [23]. Compared with spring, the DO in summer was 1.57 mg/L lower, while the DO increased by 0.83 mg/L in the autumn. Likewise, at point A, the average DO in summer was the lowest at 4.62 mg/L, while in spring, the DO was measured at 7.05 mg/L, with an increment of 2.44 mg/L compared with summer. The average DO measured in autumn was 6.45 mg/L, a 1.83 mg/L increase over the summer DO level. The seasonal comparison of the DO concentration at points A and B revealed a 63.8% DO increment from

2.55 mg/L to 7.05 mg/L in spring and a 78.6% DO increment from 0.98 mg/L to 4.62 mg/L in summer. In autumn, it was observed that the DO increased by 71.8%, from 1.81 mg/L to 6.45 mg/L. The reason for the seasonal variation in the dissolved oxygen concentration is attributed to the increase in bacterial diversity in warmer months [24] and the decline in oxygen solubility due to an increase in the temperature of the stream.

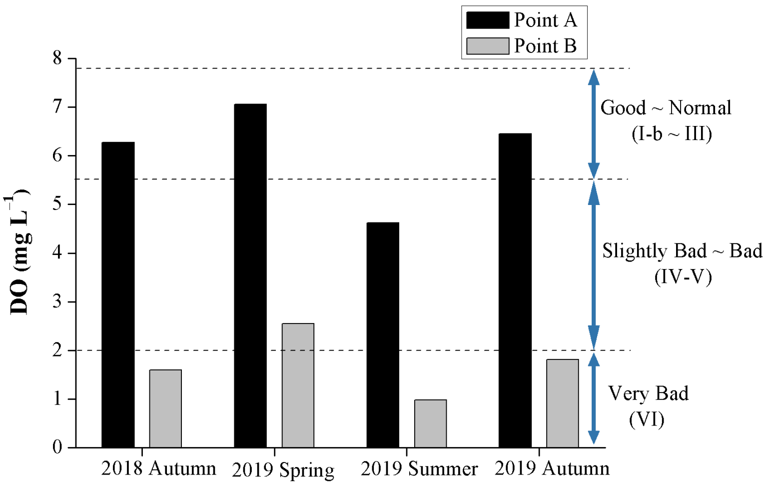

Figure 5. Variation in dissolved oxygen (DO) content over different seasons in the field experiment.

Furthermore, although there was seasonal variation, it is important to observe that dissolved oxygen could be significantly improved from the very bad to good grade when the stream water was cycled through the installed MVA system at point A. It is evident from the plot in Figure 5 that compared with point B, the average DO concentration increased by 3.5 times at point A in the presence of the MVA system. The results indicate that when the MVA is employed, the increase in dissolved oxygen concentration is significant in contrast with point B.

3.1.2. Complex Odor

The data for variation in seasonal complex odor were recorded for a period of one year (Figure 6a). At point A, the average of the complex odors measured in the autumn of 2018 was the highest at 10.19, and the average of the complex odors measured in the spring of 2019 was 5.67, suggesting a 44.7% decrease from the autumn of 2018. In summer, the average odor was 8.51, which was reduced by 24.8% in the autumn of 2019. In addition, comparing the autumn of 2018 and the autumn of 2019, the complex odor in the autumn of 2019 was 6.46, indicating a 36.6% reduction.

At point B, where the MVA system was not installed, the average complex odor was 23.91 in autumn 2018, 17.74 in spring 2019, 33.22 in summer 2019, and 22.98 in autumn 2019, with the highest value observed in summer. Overall, a negligible reduction of 3.87% in complex odor was noted when comparing the autumn values of 2018 and 2019.

It is imperative to compare the complex odor between points A and B to determine the efficiency of the MVA system in complex odor reduction. Comparing the complex odor by season, in the autumn of 2018, there was a 57.4% decrease, and in the spring of 2019, there was an almost 68% reduction. In the summer of 2019, there was a 74.4% reduction in complex odors, and in the autumn of 2019, a reduction of 71.9% was observed. In addition, it was observed that the complex odor varied by season, and comparing the values for 2019 alone, the complex odor was observed to be lower in spring and autumn than in summer. Increased temperatures in summer can further degrade water quality and increase the degree of black odorous water by influencing the release of phosphorous from sediments [25,26]. Therefore, the findings highlight that the odor was very strong at point B in all the seasons, particularly in summer, and the effect of odor reduction was investigated. Comparing the autumn of 2018 and the autumn of 2019 (after the installation of MVA system), it is apparent that the decrease in complex odor was greater after one year of system operation. Notably, it was confirmed that TON and complex odor decreased as dissolved oxygen increased (Figure 6b,c). A correlation analysis was performed using SPSS v. 22.0 to estimate the degree of association among multiple variables, including DO, TON, and complex odor, and a correlation matrix was computed (Table 2). The table shows the degree of linear association between any two of the parameters, which is measured by the degree of correlation as a coefficient (R). The R-values indicate the highly correlated inter-relationships between DO, TON and complex odor. The confidence interval was 95% and the significance level was $p < 0.05$. It was observed that the TON and complex odor are negatively correlated with DO because with an increase in DO, the complex odor as well as TON decreases. The circulation of the water through the MVA system provides enough dissolved oxygen (~22 mg/L) to the aerobic bacteria so they can actively break down the odorous compounds, resulting in odor reduction [27].

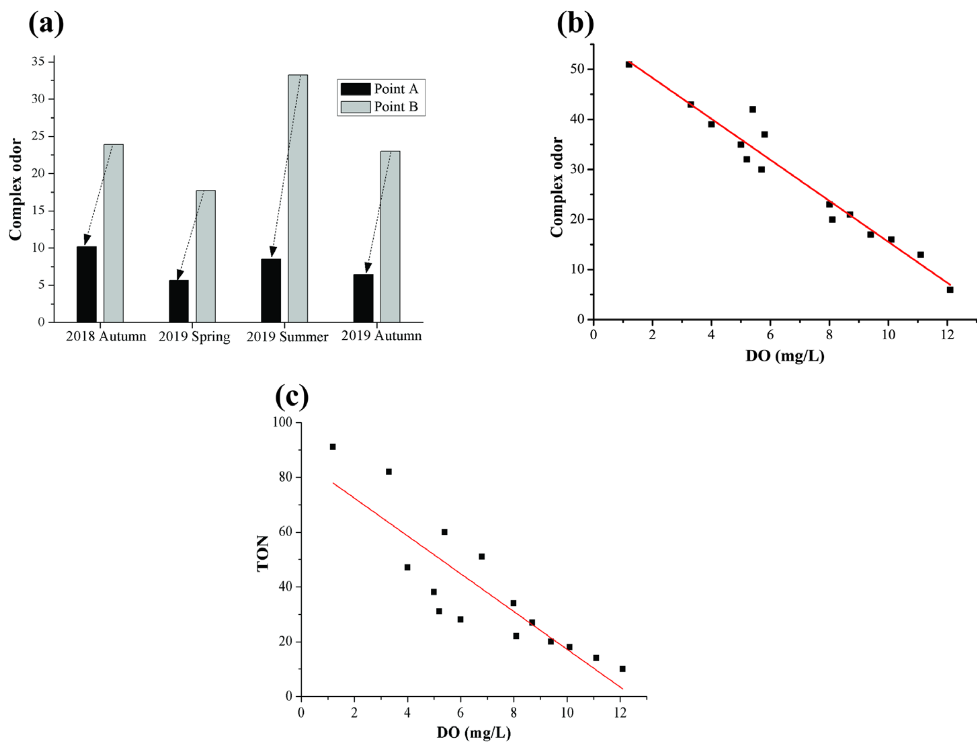

Figure 6. (**a**) Complex odor at point A and point B according to seasonal variation; (**b**) influence of dissolved oxygen (DO) on complex odor; and (**c**) effect of DO on TON.

Table 2. Correlation matrix of the important parameters.

	DO	TON	Complex Odor
DO	1	−0.8744 **	−0.9649 **
TON	0.8744 **	1	0.9186 **
Complex odor	0.9649 **	0.9186 **	1

Note: **: *p*-value < 0.05.

3.1.3. Water Quality Analysis

The descriptive statistics of the experimental data of water quality parameters at points A and B over the given period are presented in Table 3.

Table 3. Descriptive statistics of the water quality parameters.

	Min	Max	Average	STD
T-N at point A	0.300	4.510	2.10552	1.216509
T-N at point B	0.530	4.810	2.52828	1.189926
T-P at point A	0.005	0.045	0.01529	0.009180
T-P at point B	0.020	0.060	0.03510	0.011119
COD at point A	5.150	19.140	14.67156	2.835519
COD at point B	6.220	19.960	16.63875	3.201404
SS at point A	2.667	25.000	14.25950	6.083765
SS at point B	8.000	136.700	36.44611	28.228620

At point A of zone 1, the average total phosphorus (TP) concentration was measured at 0.015 mg/L and it was 0.035 mg/L at point B of zone 2, indicating a 56.4% reduction. The significant removal of TP could be attributed to the enhanced DO concentration due to the presence of the MVA system, which can promote aerobic microbial growth, resulting in accelerated phosphorous consumption [28]. There is a strong possibility that the product of the decomposition of the organic matter facilitated the deposit and subsequent adsorption of the phosphorous onto the sediments [29,30]. Urban streams are more susceptible to eutrophication because of their lower self-purification capacity than rivers. Therefore, from the environmental perspective, it is importance to prevent the accumulation of nutrients causing eutrophication. During the field experiment period, the water quality grade, based on the average TP concentration, gradually improved from bad to normal. Overall, it improved from a very bad to good grade at the end of the treatment period (Figure 7a).

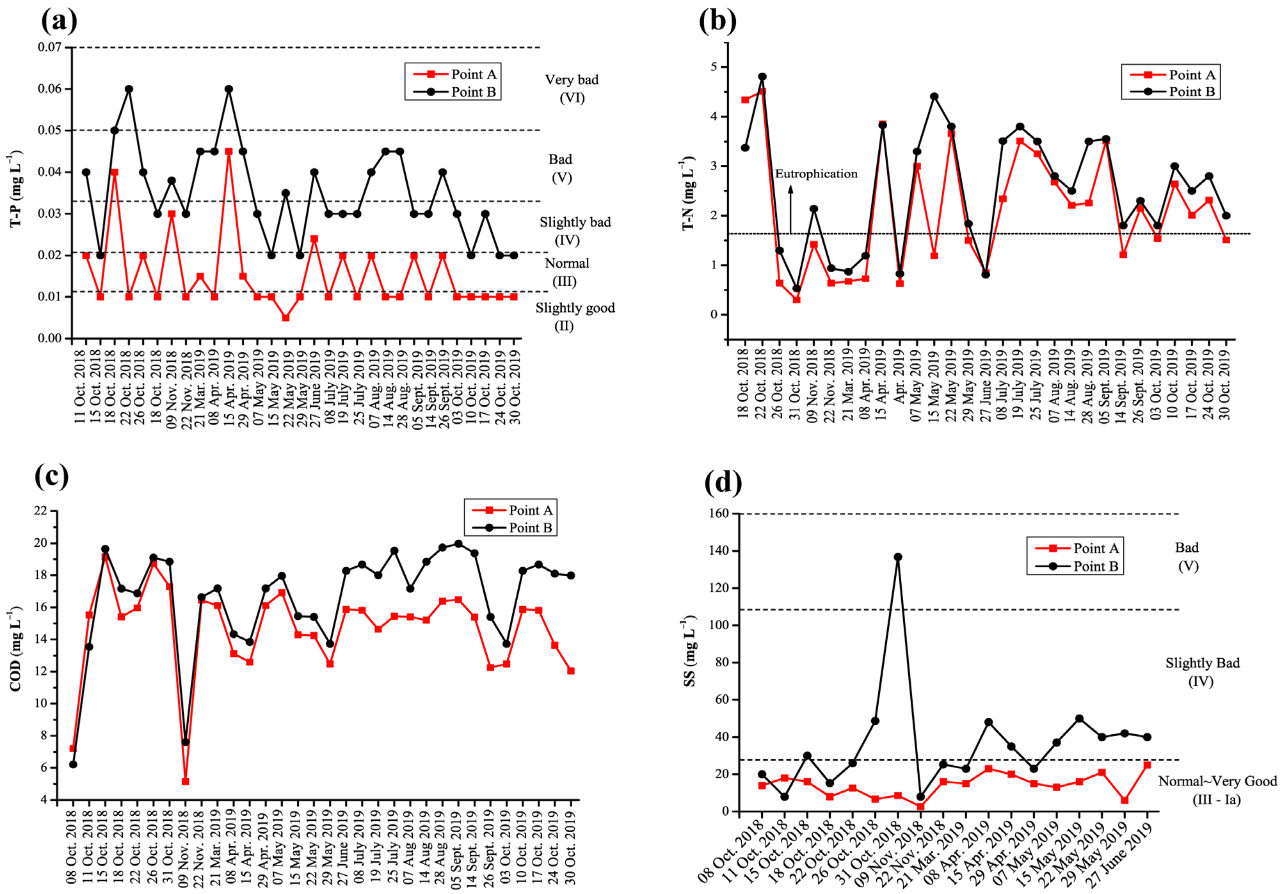

Figure 7. (**a**) Field experiment total phosphorous (T-P) concentration variation over time; (**b**) total nitrogen (T-N) concentration variation over time; (**c**) COD concentration variation over time; (**d**) suspended solids (SS) content variation over time.

Total nitrogen (TN) was also compared and analyzed at point B of zone 2 and point A of zone 1, where the MVA was installed. The TN concentration over a period of one year ranged from 0.3 mg/L to 4.81 mg/L, depending on the seasonal variation (Figure 7b). Total nitrogen was reduced by up to 17% on average at point A compared with point B. The aerobic conditions promoted by the application of the MVA aid the microorganisms in nitrogen removal by oxidation of anaerobic ammonia.

The chemical oxygen demand (COD) was compared at point A (having high DO) of zone 1 with point B of zone 2 (Figure 7c). The COD was influenced by the tide and displayed a range of concentrations. Based on the analysis of a year of data, it was observed that the average chemical oxygen demand at point A of zone 1 was reduced by up to 12% compared with that at point B in zone 2. The increase in dissolved oxygen stimulates the microbial activity, where the microbes decompose and consume the particulate organic matter (POM), thereby lowering the chemical oxygen demand [31].

In the presence of the MVA system at point A, the suspended solid (SS) concentration was reduced by 61% on average compared with point B (Figure 7d). Overall, the water quality improved from a poor to moderate grade and from a moderate to very good grade after circulation through the MVA system over a period of twelve months. Pure oxygen (~90%) injection and multistage mixing through the MVA enhanced the dissolved oxygen content and augmented the biological decomposition of organic matter, thereby reducing the suspended solids concentration.

The above findings demonstrate that the MVA system enhances the dissolved oxygen and thereby reduces the concentration of pollutants in odorous water by stimulating the growth of microorganisms.

4. Conclusions

In this research, we evaluated the feasibility of installing and operating the MVA in Goejeongcheon stream, Saha-gu, Busan, from September to November 2018 and March to November 2019. The novel MVA system is an in situ remediation technology that efficiently transfers and increases the dissolved oxygen in the water body, thereby promoting aerobic microbial activity. The proposed MVA process was monitored for nearly twelve months and demonstrated promising results, with a 3.5-times increase in DO content and maximum removal rates of TP and SS of 56.4% and 61%, respectively. Several water quality indicators met the Class Ia (very good) standard, while others achieved the Class Ib (good) surface water standard.

The present work demonstrates that by increasing the dissolved oxygen concentration, it was possible to reduce odor sources and improve the water quality of the polluted research site. The MVA system can be operated in a continuous mode devoid of any fouling problems. It can be a viable alternative to treat odorous water bodies through pure oxygen injection. It is reported as the first case in Korea and worldwide of improving the odor and water quality of a stream by employing a multistage vortex aerator (MVA). Overall, the effects of increased dissolved oxygen on odor reduction and water quality parameters (T-N, T-P, COD, S-S) are documented and discussed in this paper. Based on the results, the proposed system can be developed into a full-scale river purification system in the future. The findings of this work provide valuable insights that can be applied in scaling up the system in future studies. However, for the large-scale application of this technology, the production cost of pure oxygen and the durability of the equipment need to be examined in detail.

Author Contributions: Conceptualization, S.P.; methodology, M.C.; software, J.K., S.K. and A.G.; validation, J.K.; formal analysis, A.G. and D.Y.; investigation, M.C., S.K. and D.Y.; resources, J.-J.Y.; data curation, M.C.; writing—original draft preparation, A.G.; writing—review and editing, S.P.; visualization, A.G. and S.K.; supervision, S.P.; project administration, J.-J.Y.; funding acquisition, J.-J.Y. and S.P. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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