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Field trial of water flow and ultrasonic irradiation to improve the water quality of a stagnant river reach

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ABSTRACT

Even though lab-scale ultrasonic irradiation has successfully improved water quality, the few field applications of this environmentally friendly solution have shown mixed results. In this work, jet water flow and ultrasonic irradiation with a 200-kHz frequency were integrated to study the effect of the system operation on the water quality of a stagnant Yeo-cheon River section. Samples were continuously collected only under jet flow and then under the combined system for 2 and 10 weeks, respectively. In general, the integrated system showed a localized improvement in the water quality in terms of Chlorophyll-a (Chl-a) and dissolved reactive phosphate. Dissolved oxygen (DO) increased by more than 100% at 5 and 25 m, and increased in average by 60% further downstream. Even though flow was expected to suspend the sediments and increase turbidity, in the combined treatment, there was no increase, which was likely due to the agglomeration and settling out of particles due to sonication. However, the nitrogen and dissolved organic carbon concentrations showed a fluctuating trend. The inverse association between DO and Chl-a decreased from a coefficient of 0.51–0.37 when the ultrasonic irradiation unit was coupled with the flow, which resulted in a reduction effect on the Chl-a concentration from ultrasonication. The relationship between DO and reactive phosphate also indicated a higher influence of ultrasonication than flow on the phosphorus concentration. In general, the cumulative effect of the water flow and ultrasonic irradiation met the water quality requirement of the river for a healthy ecological interaction.

Keywords: Stagnant; Ultrasonic irradiation; Water flow; Water quality

1. Introduction

Human activities put freshwater quality at risk, mainly due to the expansion of agriculture and industries, damming, diversion, and the discharge of inadequately treated wastewater. It has been stated that 2 million tons of sewage, industrial waste and agricultural waste are released into the world's water every day [1]. Rapid human population growth and climate change, especially global warming and the spatial and temporal variations in rainfall with increased severity of droughts and floods, have escalated the problem [2–4].

Merel et al. [5] discussed that eutrophication of water resources is the primary cause of global surface water quality problems. Eutrophication causes biological problems as a result of the death of oxygen sensitive species, creating problems by clogging the filtration unit in treatment plants, economic losses due to the cost of the required monitoring program, additional operational costs, and a reduction in the revenue from agriculture and fishing along with reduced recreational uses and social problems resulting from the release of undesirable odors, colors and toxins [6–9].

In drinking water treatment, to protect consumers from cyanotoxins and to make the water aesthetically fit, high capital and operating cost demanding techniques, such as advanced oxidation or adsorption, are applied [5,10].

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In addition, to address the ecological consequences of water quality impairment, efficient protection and monitoring of the source water are of critical importance. This primarily involves controlling the point and non-point sources release of nutrients, especially nitrogen and phosphorus, into the receiving water bodies [11].

In developed countries, through wastewater treatment facilities, point nitrogen and phosphorus sources are more or less effectively controlled. However, controlling the diffuse or non-point sources, which are mainly from agricultural and construction activity runoff, abandoned mines and atmospheric deposition, is more difficult and will only be effective long term [12]. In the USA, the broad Total Maximum Daily Load (TMDL) program is applied to control non-point sources [13], and in Europe, freshwater-related legislation, mainly the Water Framework Directive (WFD), addressing at least one aspect of nutrient pollution is applied to attain a good ecological status [14]. In Japan, total pollutant load control reduction targets are applied over all the related catchment areas when the waters do not meet the environmental quality standards [15]. Similar attempts are made elsewhere, especially in developed countries, to monitor changes in the nutrient loading and the responses of aquatic ecosystems to the changes [8].

Even though the only long-term solution to controlling water quality is to restrict nutrient inputs into the water bodies, immediate results may not be obtained because the nutrients stored in the sediments of the water are often released to the water column under a favorable environment [16]. Hence, external source control mechanisms should be coupled with internal control strategies to obtain a holistic approach. The water quality management techniques applied to control algae and related water quality problems in a stagnant water body can be grouped into chemical, physical, biological methods as well as combined strategies.

The chemical methods have associated toxicological risk to non-target organisms, persistence in the environment and high costs [17–19]. Biologically derived substances have high preparation costs; they possibly damage non-target aquatic organisms; and they sometimes have low algae removal efficiency [20]. Although the physical approaches have less secondary pollution in the ecosystem, they are energy intensive, which is often associated with injury to non-target organisms. Studies on in-water sediment treatments and phosphorus inactivation show mixed results. Dredging is expensive and requires safe handling of the sediments; there are often difficulties in creating a uniform and continuous layer under the water in sediment capping; there should be sufficient inflow to replace the hypolimnetic withdrawal; and phosphorus inactivation is very much case sensitive [16].

Since each method has pros and cons, a search for an alternative and effective solution with a reasonable balance is still ongoing. Systems are often combined to maximize the water quality improvement and cyanobacterial biomass removal [21–29]. This study also combined strategies, including using a water flow generator and an ultrasonic irradiation unit, to assess the potential of the system to improve the field-scale water quality. Even though there are a large number of studies on the control of blooms and the improvement of water quality using ultrasound [30], only a few field studies are available published as peer-reviewed literature. The field studies stated deterioration of some of the water quality variables, and an effective method is still being researched [31].

A water flow generator unit allows river water to move; hence, the stagnancy-related deficiency of dissolved oxygen (DO) at the sediment layer and accompanying water quality issues will be impacted. On the other hand, ultrasonic waves affect phytoplankton by collapsing the gas vesicles that keep them floating and reduce the cell integrity, viability and photosynthetic activity [32]. In addition to being a non-chemical strategy, if a solar and/or wind energy source is considered to reduce the related operation costs [33], the system will be a green technology.

In 2006, two devices that are similar to the one considered in this study, except that an ozonation unit is not used here, were installed in the Yang Min Lake on Kinmen Island, Taiwan, to determine the effect of the units on the cyanobacteria population and the physical and chemical changes they caused [10]. The units failed to achieve the target due to high cyanobacterial cell counts. The present study aimed for physical and chemical water quality improvement to prevent algal bloom formation in a stagnant Yeo-cheon River reach (Korea), which has recently shown signs of water quality problems such as scum formation and fish death. The river water quality was monitored, especially the Chlorophyll-a (Chl-a) and DO concentrations, for 3 months. The water flow generator was operated alone for half a month, and then, the ultrasonic irradiation device was coupled with the flow unit for the remaining duration of the experiment. In addition to assessing the water quality improvement, the correlation among the parameters was analyzed to explain the contribution of ultrasonication.

2. Materials and methods

2.1. Study site and sampling points

The Yeo-cheon River flows through Suwon city, Gyeonggi province, South Korea, before emptying its content into the Woncheon Reservoir. The reservoir (37°16′51″ N and 127°03′46″ E), which has a surface area of 8.96 km^2 and a volume of 198.8 × 10^3 m^3, was established to secure water for agricultural use [34]. However, it has now become a major recreation center after the development of a park and apartment complexes in the vicinity.

The sampling positions were determined relative to the water quality improvement device location (37°17′11″ N and 127°03′41″ E) in the river (average depth of 1.5 m) at a stretch in the mouth to the Woncheon Reservoir and in the reservoir itself (Fig. 1). Specifically, samples were collected, at 50 and 25 m upstream of the device position and at 5, 25, 50 and 100 m downstream of the device location. The upstream locations were considered to represent the area not subjected to the unit. The data and sample collections were made weekly near the middle of the specific site water column at all the sampling points. Except at the 100 m position, samples were also taken from the top (5 cm below the water surface) and the bottom (10 cm above the sediment) layers at the downstream points.

The river quality was monitored for the effect of the flow and ultrasonication device operation at the six different points from August 31 to November 24, 2015, comprising eleven water quality parameters. The period was chosen

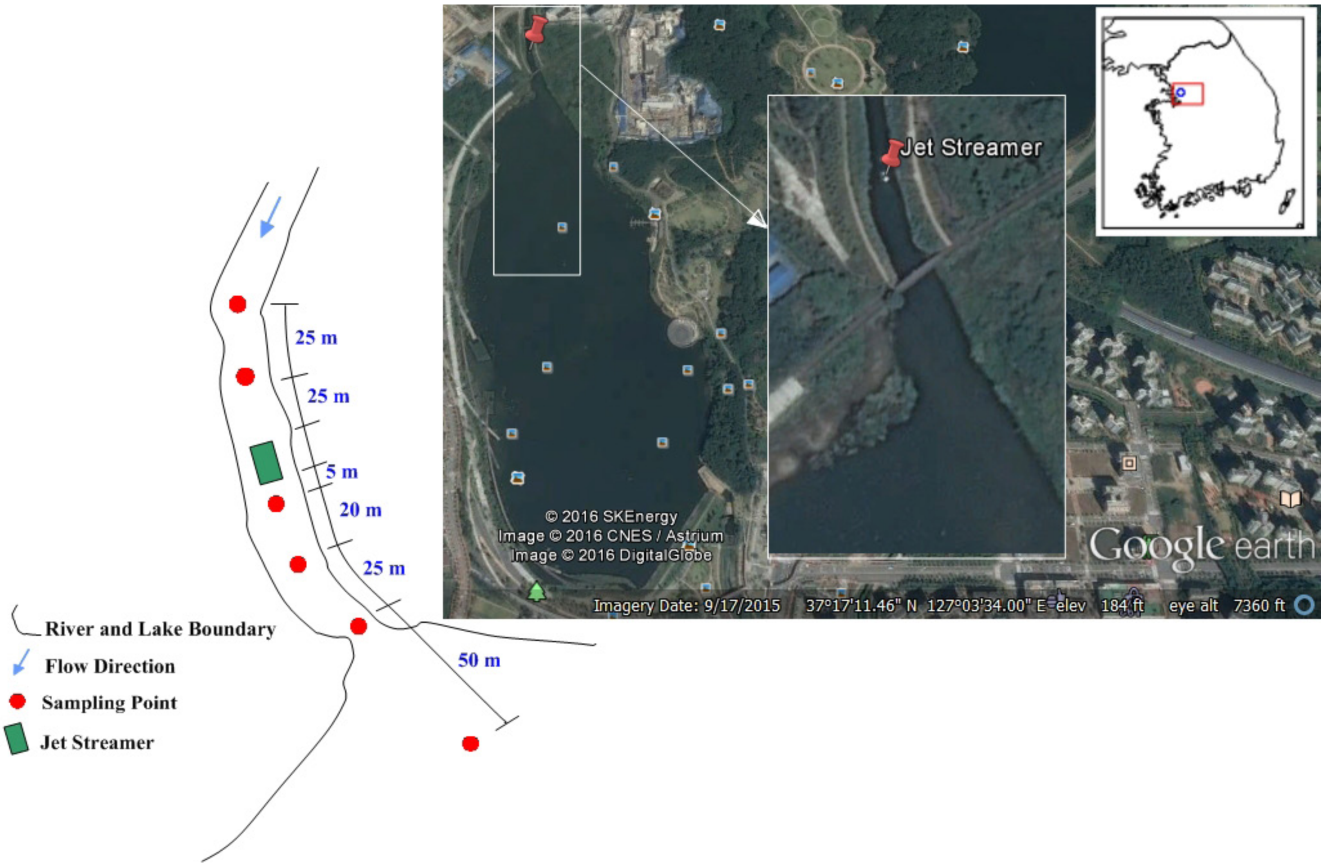

Fig. 1. Location of the six sampling points in Yeo-cheon River at the mouth of Woncheon Reservoir, Korea (the Google earth image is used based on the concept of 'fair use').

because it corresponds to the cyanobacteria bloom season in Korea [21]. The parameters were selected due to their implication for water quality problems related to algal blooms. The selected water quality parameters included temperature (T, °C), pH, flow rate (V, m/s), turbidity (NTU, Nephelometric Turbidity Units), DO (mg/L), Chl-a (μg/L), dissolved organic carbon (DOC, mg/L), total dissolved nitrogen (TDN, mg/L), ammonia nitrogen (NH_3-N, mg/L), total dissolved phosphorus (TDP, mg/L) and phosphate phosphorus (PO_4^{3-}-P, mg/L).

Temperature, DO and pH were measured in the field during sample collection using M-100, and Chl-a was measured using chlorophyll probes (Technology and Environment Corp., Korea). The flow was also determined in situ using a MiniAir 20 flow sensor (Schiltknecht, Germany). The turbidity was measured in the lab using a turbidimeter (HACH Company, USA). NH_3-N, TDN, PO_4^{3-}-P and TDP were all determined in the laboratory using a DR/5000 spectrophotometer (HACH Company, USA) after filtering the water sample through 47 mm glass microfiber filters (Whatman Ltd., UK) since turbidity and color may cause inconsistencies in the results. The DOC concentration was determined by high-temperature combustion on a TOC-V CPH analyzer (Shimadzu, Japan).

The total phosphorus and nitrogen concentrations are generally considered to show the trophic status of a water body, instead of just the dissolved inorganic phosphate or dissolved inorganic nitrogen. Ammonia is often the primary form of dissolved N in an aquatic system, and it is the major form used for algal growth. Similarly, orthophosphate represents the soluble reactive phosphate, which is the only phosphorus compound readily available for algal uptake without further breakdown. On the other hand, by measuring Chl-a, the condition of the water body with respect to blooming is often monitored. The concentration of DO in natural water generally governs the factors that may lead to blooms.

2.2. *The in situ water quality control device and its operational conditions*

The water quality improvement device was composed of a water flow generator (capacity: 70,000 m^3/d) and ultrasound irradiation units (three sets with 200 kHz oscillating frequency) based on an electric energy supply. The equipment was floated on the river water surface with a slip prevention floor and was secured to the banks of the river with chains. Water was pumped from the surface and injected into a polyvinyl chloride flow duct to drag the surrounding area water. The overall length of the rectifier tube was 2,000 mm with an inner diameter of 300 mm. The multiple ultrasonic transducers, each 160 mm in diameter and 45 mm in thickness, were placed just to the upstream of the water flow generator duct.

The jet streaming functioned in such a way that the centrifugal pump (discharging at 3 m^3/min) provided the driving force to the water ultrasonically irradiated by the submerged transducers. Thus, 70,000 m^3 of dynamic water get in contact with ultrasonic irradiation in a day within the water flow duct before discharged to the downstream. The effective ultrasonic irradiation contact time with the water was during the mechanically mixing in the duct due to the dragging effect of the pump.

The impact of flowing the stagnant water was assessed from August 31 to September 15, 2015, and then, the flow and ultrasonic radiation were operated continuously in combination until November 24, 2015. The application of the ultrasonic waves affected the floating and suspended phytoplankton in such a way that their gas filled vesicles were ruptured and their vacuoles collapsed, hence eliminating their floating advantage. The water circulation exposed the escaped untreated phytoplankton to the device during the early cycles, making the system more efficient. An oxygen-rich water layer was expected to be formed over the sediment, subjecting the treated and sedimented algae to strong oxidization and aerobic digestion processes [35,36].

3. Results and discussion

3.1. Effect of the system operation on the river water quality parameters

Data from the field study did not show a consistent overall effect for most of the water quality variables considered during the unit operation. However, some effect from the combined system was clearly illustrated on the DO and Chl-a. Because 50 m upstream was far from the area of device impact, the results from this location were excluded, and at 100 m downstream, there was a limited impact, so this location was considered for comparison. The water velocity was only 1 cm/s before the treatment started, and due to the flow generator, it was increased to an average value of 20 cm/s at the 5 m location. However, this value quickly diminished further downstream, with an average value of 5 cm/s at the 25 m position. Except for two occasions impacted by rainfall, the turbidity remained more or less the same in the device influence area.

Since the water depth considered in the study was shallow, with maximum depth of 2 m, the initial temperature variation was limited to 2°C between the water surface and the layer above the sediment. The temperature of the water column became more uniform (result not shown) mainly due to the water circulation, which was triggered by the flow generator.

Fig. 2 shows that the Chl-a concentration was maintained at low concentration near the device, but it greatly increased further downstream. Chl-a is generally used as a major water quality parameter to reflect water bloom occurrence [37]. The value was limited to below 7 μg/L throughout the treatment duration within the 25 m distance, while it increased to 18 and 41 μg/L in October at the 50 and 100 m distances, respectively. In the meantime, the concentration of Chl-a increased slightly close to the device compared with the values before the water treatment. Algae may rapidly use nutrients that are added to water body during small rainfall events and may undergo proliferation [38]. Thus, less frequent rainfall in the later days of the study may strengthened algal growth. However, as a field trial, other complex causes of the Chl-a fluctuation in shallow water bodies, such as water residence time and sediment-water nutrient exchange, cannot be excluded. Close to the device, the Chl-a increase was possibly limited by the ultrasonic irradiation effect.

Fig. 3 illustrates the percent increase of DO at the different sampling locations during the combined unit operation. DO generally increased during the treatment until November 3, 2015. The intense rainfall during the first week of November 2015 and the strong wind 2 d prior to the November 9 sampling possibly affected the results, as seen from Figs. 2 and 3. There was a significant increase in DO near the device in the downstream direction, with a concentration increase to 11 mg/L from an initial value of ~5 mg/L. This is shown in the graph as more than 100% increase, for 5 and 25 m in the upstream. The effect diminished as the distance from the device increased. The increase in DO was due to the water flow, which allowed aeration, and the insignificant change in the flow rate at the upstream and further at the downstream caused the weak increase at those points. The oxygen evolution rate decreased because of the ultrasonic effect following a decrease in Chl-a. However, the contribution of circulation and aeration by the water flow kept the concentration very high.

Generally, the Chl-a concentration decreased slightly from the corresponding initial values, especially 5 and 25 m downstream from the device during the field trial (Fig. 4). Because the initial Chl-a amount was not very high, the ultrasonic

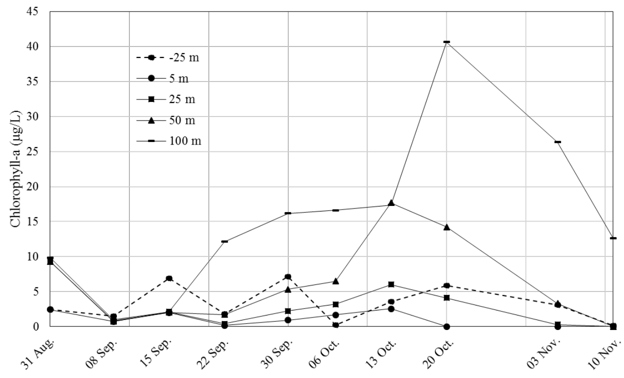

Fig. 2. Variation of Chlorophyll-a (Chl-a) at mid-depth of the stagnant river, just before and during unit operation (the broken and solid lines represent upstream and downstream of the device, respectively).

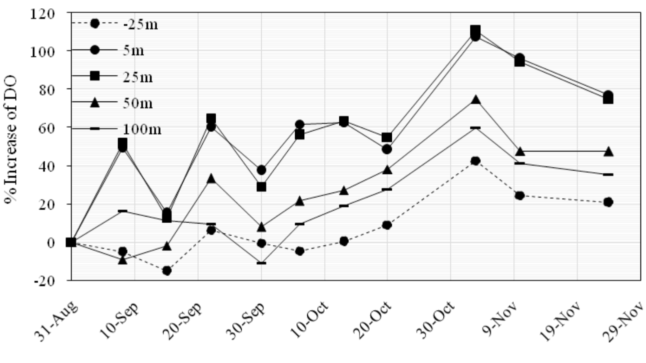

Fig. 3. Percent increase of dissolved oxygen (DO) during the unit operation at all the sampling stations (the broken and solid lines represent upstream and downstream of the device, respectively).

irradiation could reduce the concentration closer to the device as time elapsed [39]. The figure depicts that the Chl-a removal was effective throughout the water column. At 50 m, the decrease in Chl-a from the surface was limited, showing that ultrasonication only addressed the area close to the device.

Since the average depth of the river reach considered in this study was only 1.5 m, the increase in DO could be uniform throughout the water column (Fig. 5). The 5.5 and 4.7 mg/L values at the surface and bottom before the treatment were increased to 11.5 and 10.9 mg/L, respectively, 5 m from the device. The increase was also significant at the other locations. Hence, the bottom layer aeration was effectively addressed.

As far as the river water nutrient concentration was concerned, there was no clear changing trend in all the conditions. Fig. 6 shows the typical variation in TDP and filterable

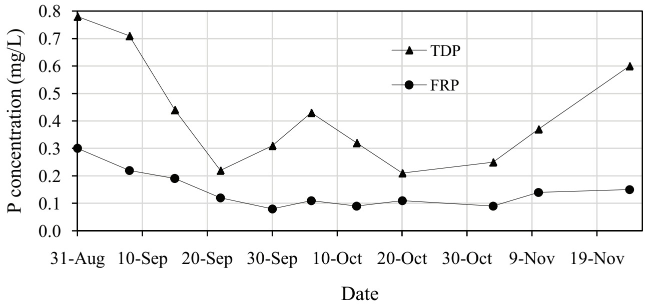

Fig. 6. Typical weekly change of total dissolved phosphorus (TDP) and filterable reactive phosphate (FRP) during the device operation at 5 m distance.

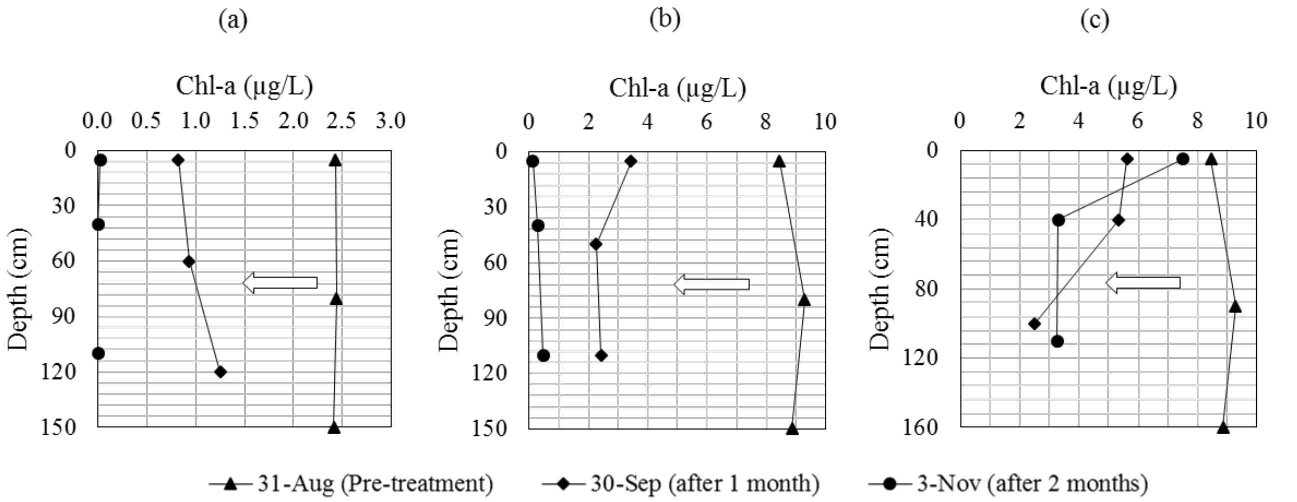

Fig. 4. Significant reduction of Chl-a throughout the water column at: (a) 5 m, (b) 25 m and (c) 50 m from the unit in the downstream.

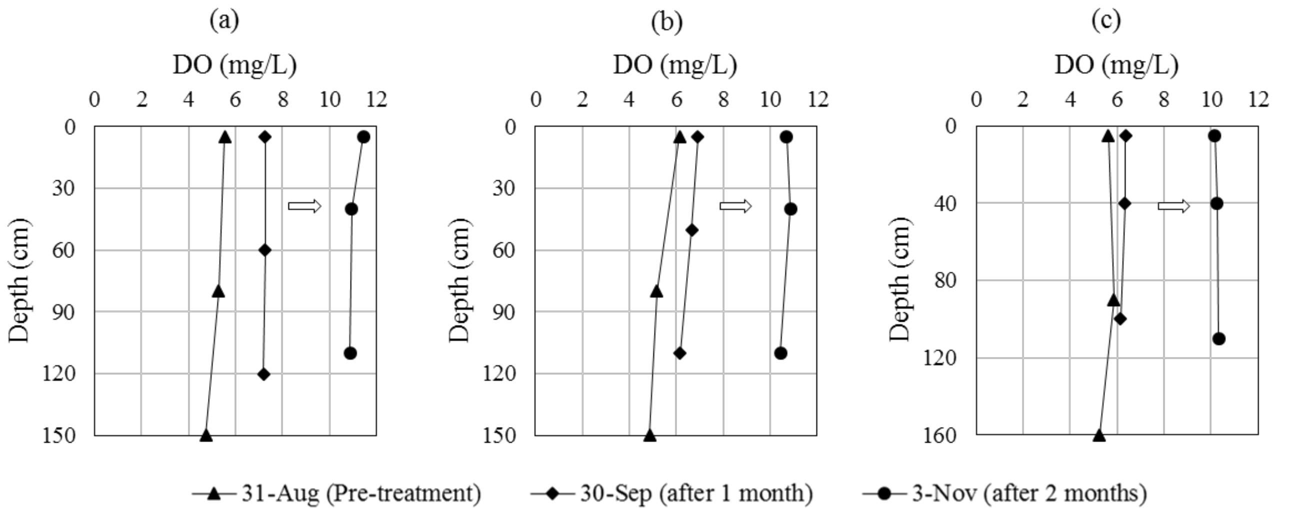

Fig. 5. Increase in DO profile during the device operation throughout the water column at: (a) 5 m, (b) 25 m and (c) 50 m from the unit in the downstream.

reactive phosphate (FRP) during the whole experiment 5 m from the device. Unlike the increase in phosphorus in sonicated pond enclosures [40], in this study, the reactive phosphate decreased by more than 50% from the initial value, which was possibly due to the increase in the oxygen bound soluble phosphates to minerals; however, the TDP showed mixed states. Basically, the TDP decreased from the comparatively high initial value of 0.78 mg/L, and the increase in the month of November was likely related to the rainy and windy weather conditions, which probably caused runoff input and bottom sediment phosphorus suspension.

The pattern was similar at all the downstream locations. The decrease was possibly because the internal release of phosphorus from the sediment under low DO conditions was prevented by the improved circulation and aeration. In addition, the TDP was reduced because the phytoplankton inactivated by ultrasonication could have absorbed the substances from the water body and settled out [39]. On the other hand, there was no clear pattern regarding the effect of the combined system on the nitrogen and DOC in the water. The DOC was more or less the same until the November 3 rainfall, which was followed by an increase in concentration at all the locations.

3.2. Relationships among the water quality variables based on the operating units

Here, the associations among the different water quality variables were analyzed to explain the mechanisms that may have occurred in the quality change during the field trial. A linear regression analysis of the water quality parameters during the test in the direction downstream (at 5, 25 and 50 m) of the device is presented in Fig. 7. Only these sampling points were considered because they are under the direct impact of the unit operation. The relationships among the parameters varied based on the unit operation. In addition, some representative water quality variables were plotted to assess the contribution of the units to the water quality improvement technique.

The plots in Fig. 7 show the correlation among the water quality parameters when only the water flow generator was operated vs. when the ultrasonic irradiation was coupled to the water flow. Flow vs. the DO coefficient decreased with ultrasonication. A similar trend was observed between DO and Chl-a, as the negative correlation coefficient magnitude decreased from 0.51 to 0.37 when the ultrasonic irradiation unit was used with the flow. This was because the ultrasonic treatment reduced the Chl-a concentration and inhibited photosynthesis, which was followed by a reduction in the oxygen evolution [37,41].

When the ultrasonic irradiation was applied, the change from a negative correlation to a positive correlation with a higher magnitude between DO and FRP indicated that there was a higher influence from ultrasonication than from flow on the FRP concentration. In addition, the decrease in Chl-a was strongly associated with an increase in FRP during sonication, which exhibited a reverse relation at a weaker magnitude for only water flow (Fig. 7(f)). During the collapse of the phytoplankton, the organic phosphates broke down, and orthophosphates were released [42]. However, the low association between DO and TDP remained unchanged. The variation in DOC with turbidity was canceled out when ultrasonication was applied, which was possibly due to a decrease in Chl-a.

Fig. 7(e) shows that the slight and negative linear relationship between Chl-a and turbidity was changed to a high positive correlation, showing that ultrasonic irradiation was the possible cause for the reduction in Chl-a and the turbidity of the water during the combined flow and sonication process. Ultrasound disrupted the gas vesicles of the phytoplankton, and then, the sedimentation of the malfunctioning phytoplankton decreased the turbidity. Doosti et al. [43] and Mutiarani et al. [44] studied the ultrasonic waves that resulted in collisions between the particles due to the molecular vibration induced by their irradiation; then, the particles settled at the bottom. From the coinciding change in turbidity with that of the Chl-a concentration, it was expected that the main part of the turbidity was contributed by the Chl-a concentration in the water column. In addition, a weaker association between the flow and turbidity was signified under the combined system (Fig. 7(h)). In the combination of sonication and circulation study done by Ahn et al. [21], the turbidity of the treated pond increased; however, the initial turbidity was maintained in the present study.

3.3. Relationships among the water quality variables considering depth

Fig. 8 presents the association among typical water quality variables to describe the variation from layer to layer for the combined system. What actually occurred at the sediment–water interface was too complex to be certain about. However, it was apparent that aeration enables iron to bind phosphorus in sediment. Turbulence may increase the soluble reactive phosphate. In addition to the oxygen and sediment iron state, pH also plays a role in phosphorus immobilization. The impact of ultrasonic irradiation on phosphorus can be linked to its effect on Chl-a.

Jin et al. [45] found that in an alkaline condition, the rate of phosphorus release increased with an increase in pH. In this study, the pH generally decreased from a maximum of 8.8 to a minimum of 7.2 from the surface to the bottom possibly due to higher decomposition, which decreased the photosynthesis and other chemical reactions at the bottom. The change in pH may affect the solubility of the phosphorus, making it more available and resulting in a greater demand for DO. DO also decreased with increasing depth because of the atmospheric aeration at the surface, and DO was supposed to be consumed more at the bottom due to decomposition. However, Fig. 8(c) shows that the TDP–DO association was independent of depth in the combined treatment.

Fig. 8(d) shows that Chl-a marginally increased the turbidity in the upper water column compared with the bottom layer, as the suspended sediments likely constituted a larger part of the bottom layer. On the other hand, Chl-a exhibited a weak correlation, which comparatively decreased as depth increased, with TDP, and the vertical location in the water column seemed to have a slight influence on the association between DO and Chl-a. The removal of the Chl-a suspension from the water column by the ultrasonic irradiation effect added to a higher DO demand at the bottom instead of the natural purpose of offsetting the oxygen loss due to photosynthesis.

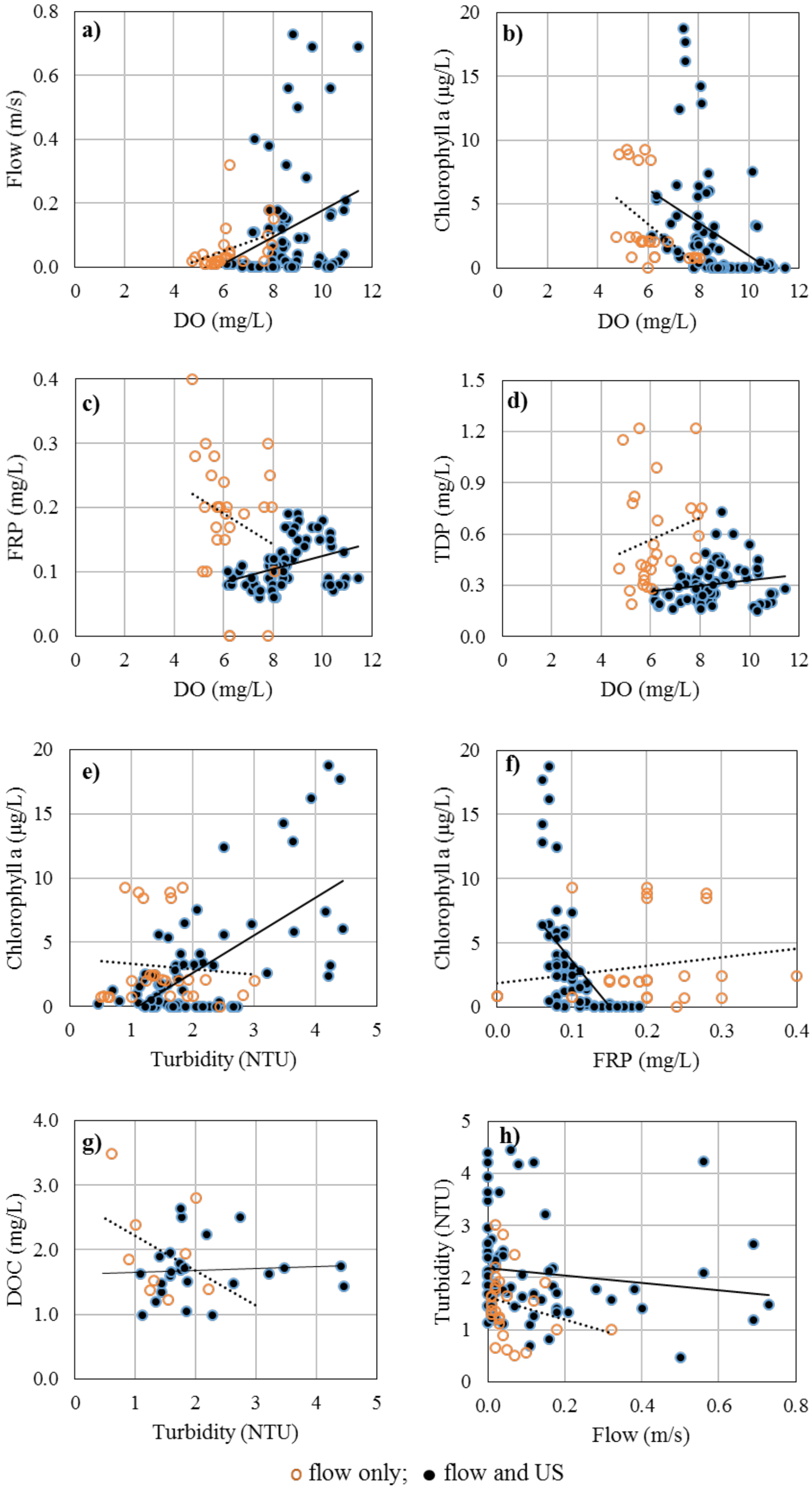

Fig. 7. Relationships among water quality parameters when only flow unit operated ($n = 27$) and the flow coupled with ultrasonication, US ($n = 72$): (a) to (d) DO vs. flow, Chl-a, FRP and total dissolved phosphorus (TDP), respectively; (e) Chl-a vs. turbidity; (f) Chl-a vs. FRP; (g) Dissolved organic carbon (DOC) vs. turbidity and (h) turbidity vs. flow.

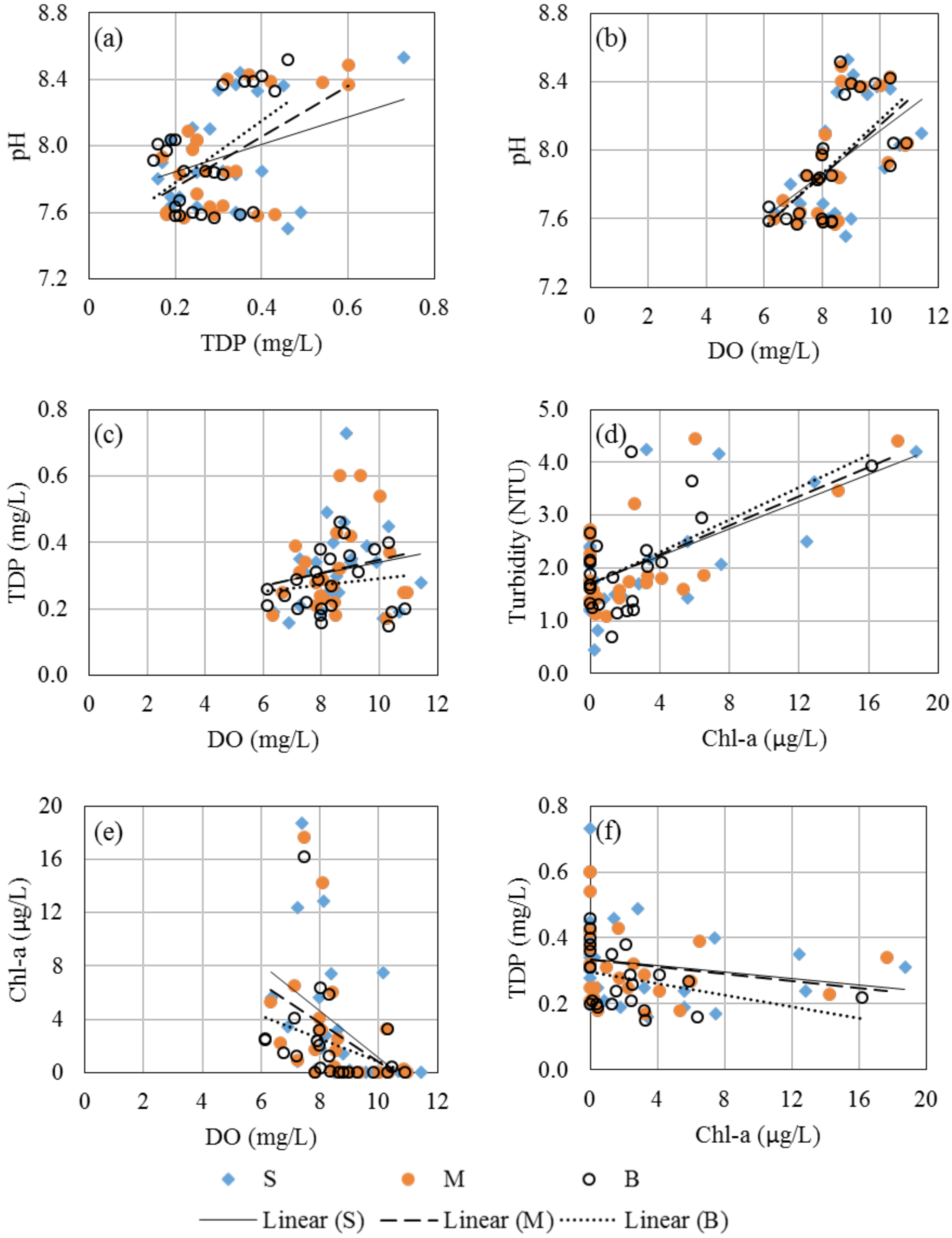

Fig. 8. Typical water quality parameters correlation at the surface (S), middle (M) and bottom (B) layers of 5 m, 25 m and 50 m locations in downstream direction (n = 24) under the combined treatment: (a) pH vs. total dissolved phosphorus (TDP); (b) pH vs. DO; (c) TDP vs. DO; (d) Chl-a vs. DO; (e) Turbidity vs. Chl-a and (f) TDP vs. Chl-a.

4. Conclusions

A field trial of the combined strategy involving water flow and ultrasonic irradiation in a stagnant river reach was conducted for 3 months to assess the applicability of the system to improving the water quality. Profiles of both the Chl-a and DO concentrations indicated that the proposed strategy seemed to be working well and that the water quality could be improved prior to the later rainy and windy days. At locations under the limited influence of the system operation, Chl-a highly increased, but within 25 m of the operation, the low initial value was maintained. However, the need for further studies focusing on different algal species is emphasized to assess in case there could be species shifting during the system operation. Even though the flow increased the turbidity by suspending sediments, ultrasonic waves canceled out the effect due to the agglomeration of the suspended particles and the following settling out.

The contribution of the ultrasonication was explained in terms of a change in the correlation among the water quality variables based on the operated units and depth of the water. The inverse association between DO and Chl-a decreased when the ultrasonic irradiation unit was coupled with the flow, showing that ultrasonic treatment reduced the Chl-a concentration and inhibited photosynthesis, which was followed by a reduction in the oxygen evolution. The relationship between DO and FRP also indicated a higher influence on the FRP concentration from ultrasonication than from flow. There was also a variation in the interaction based on the depth as the pH and DO decreased from the surface to the bottom, which played a role in the phosphorus released into the water column.

The combined effect of the water flow and ultrasonic irradiation can be taken as cumulative water quality improvement, as the flow helped increase the DO and the sonication reduced the Chl-a. The DO and Chl-a maintained by the combined unit system met the water quality requirement of the river for a healthy ecological interaction. However, the overall improvement in the water quality is not yet guaranteed because the effectiveness of the ultrasonic technology requires long-term monitoring of the water quality before, during and after treatment [46]. Even though the short duration of the study conducted here limited the nutrient pattern realization, the use of ultrasound at the field scale to improve water quality is promising. A biological quality investigation is needed for full-scale application, which will be our next work.

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