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Influence of abnormal water intake linked to underwater aeration on ceramic membrane fouling in a drinking water treatment plant in Yeoncho, Korea

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ABSTRACT

This study investigated the fouling of ceramic membranes, which led to an increase in the trans-membrane pressure (TMP) in a drinking water treatment plant in Yeoncho, Korea. The TMP values of the ceramic membranes monitored from 2014 to 2018 ranged from 0.01 to 2.12 kg f cm^{-2} (average TMP = 0.61 kg f cm^{-2}). The TMP values fluctuated significantly, and considerable differences were found for each ceramic membrane module. A high TMP value (>1.5 kg f cm^{-2}), the criterion for clean-in-place, was frequently observed, and its duration was prolonged. In addition, the TMP values remarkably increased when the water level in the reservoir decreased after increasing and when the underwater aeration within the reservoir was activated. The TMP was also related to the depth of the water intake. Comprehensive analyses of the fouled ceramic membranes revealed that organic matter, microalgae (e.g., diatom frustule), aluminum, manganese, and silica were the main components of the membrane foulants (organic material content = 48.5%; inorganic material content = 51.5%). Thus, a large proportion of the source material in the reservoir strongly contributed to the fouling of the ceramic membranes. To comprehensively explore the behavior of foulants in the reservoir and alleviate membrane fouling, minimizing artificial disturbances in the water body in the reservoir in terms of raw water management was necessary. In particular, semi-enclosed medium-sized reservoirs that supply raw water to the membrane filtration process for producing drinking water are more vulnerable to membrane fouling.

Keywords: Ceramic membrane; Fouling; Water intake; Underwater aeration; Turbidity

1. Introduction

Membrane filtration technology in water treatment is superior to conventional filtration methods [1,2]. In addition, it is challenging to develop membrane materials and modules suitable for various sources that require water treatment in the fields of life and industry [3]. The membrane filtration process using microfiltration (MF) in water treatment is new and has been introduced owing to its advantages such as high efficiency, low energy use, and relatively stable water quality and quantity compared to existing methods [4,5]. Membrane filtration in water treatment can effectively remove particulate matter such as turbidity, pathogenic protozoa (e.g., *Cryptosporidium* and *Giardia*), and microalgae, thereby producing high-quality drinking water [1,2].

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The MF membrane modules used in water treatment are generally polymer organic membranes, but in recent years, interest in ceramic membranes with high membrane permeability and mechanical, chemical, and thermal stability has increased, and these membranes have been introduced into water treatment [6,7]. The membrane filtration process using the MF membrane can secure stable water quality by removing contaminants larger in size than the pores of the membrane [8]. However, as particles and dissolved substances present in water accumulate on the surface of the membrane and reduce its permeability, problems such as an increase in transmembrane pressure (TMP) and a decrease in the amount of water to be treated may cause a decrease in the operating efficiency of the facility [9]. Thus, membrane fouling is a major problem encountered in the membrane filtration processes, and it is a major factor in determining their practical application in water treatment in terms of technology and economics [10,11].

During the membrane filtration process, various contaminants contained in the influent water adhere to or accumulate on the surface and pores of the membrane, thereby resulting in membrane fouling, which closes the pores of the membrane and reduces the filtration efficiency [12–14]. Therefore, minimizing membrane fouling is crucial. Membrane fouling can be largely divided into reversible fouling, which can be recovered by physical cleaning, and irreversible fouling, which can be recovered by chemical cleaning, although the recovery rate by physical cleaning is low [15]. The methods used to prevent membrane fouling include applying appropriate physical and chemical cleaning methods depending on the membrane material and module and reduction of membrane fouling through linkage of the pretreatment process [16]. Among them, the pretreatment process has the advantage of improving the membrane performance and delaying fouling by removing substances that may increase the fouling of the separation membrane in advance [11,17]. However, most research has focused on finding the cause and solution of membrane fouling only in water treatment plants.

Underwater aeration is one of the methods used to improve the water quality of eutrophic reservoirs. It is widely used for preventing water temperature stratification, suppressing the release of heavy metals in the sediment layer, and mitigating the growth of microalgae [18]. In particular, most reservoirs in Korea have aerators installed and operated around the water intake tower [19]. However, it was difficult to find previous studies that evaluated the effects of water intake on membrane fouling by comparing the advantages and disadvantages of underwater aeration.

The purpose of this study was to comprehensively investigate the actual conditions of membrane fouling, which occurs frequently in water treatment plants with ceramic membranes, and to determine the cause and a solution. In a water treatment plant where the filtration process was retrofitted from sand filtration to ceramic membrane filtration, the unexplained increase in TMP not only caused chronic water treatment disorders but also caused serious difficulties such as unexpected accidents that sometimes stopped the production of drinking water. The cause deviated from the inside of the water treatment plant, and the source material of the reservoir was explored. A suitable solution for membrane fouling could not be found in the results of various studies on the factors in water treatment plants in recent years; hence, the focus of this study was the excessive influx of fine particulate matter, which is detrimental to the membrane filtration efficiency.

2. Materials and methods

2.1. Description of the study area

The Yeoncho Reservoir (36°56′N, 128°40′E) and the Yeoncho Water Treatment Plant are located on Geoje Island (Geoje City, South Gyeongsang Province) on the southeast coast of Korea (Fig. 1). The dam reservoir was completed in 1979 and was created for the purpose of supplying local living and industrial water. The basin area is 11.7 km^2, the reservoir area is 4.24×10^5 m^2, and the maximum depth is 16.4 m (Table 1). The reservoir volume is 4.96×10^6 m^3, which is the only inflow river in the Yeoncho Stream. When the reservoir is filled with water, it naturally overflows through the spillway. During the summer monsoon (rainy season and typhoon), many floods introduce turbidity due to the clay and silt particles, which remain in the reservoir water for a long time or are deposited after settling.

The reservoir is equipped with four selective water intake facilities and 19 intermittent underwater aeration devices for water quality management and response to

Fig. 1. Map showing the study area of the Yeoncho Reservoir and the Yeoncho water treatment plant (WTP) located in Geoje Island, Gyeongsangnam-do, South Korea.

Table 1
General geographic and limnological features of the Yeoncho Reservoir constructed in 1979

Attribute	Yeoncho Reservoir
Latitude	34°94′N
Longitude	128°67′E
Elevation (EL. m)	48.0
Function	Water supply
Circulation type	Monomictic
Trophic state	Meso-eutrophic
Yearly precipitation (mm)	1,819
Yearly average inflow ($m^3 s^{-1}$)	0.272
Watershed area (km^2)	11.7
Reservoir area (m^2)	4.24×10^5
Impoundment (m^3)	4.96×10^6
Maximum depth (m)	16.4
Hydraulic residence time (d)	286.9
Dam height (m)	24.5
Dam length (m)	120.0
Dam width (m)	7.0

The data are mean values from 2013 to 2018.

the occurrence of harmful cyanobacteria and off-flavor materials (Fig. 2). The underwater aeration device is fixedly installed and concentrated around the water intake tower. Additionally, an underwater curtain membrane (from the water surface to a depth of 10 m) is installed in the center of the water intake tower to block the inflow of algae in a circular structure that moves vertically according to the fluctuation of the water level.

The Yeoncho water treatment plant was established in 1979 and is located just below the Yeoncho Reservoir. The daily water production is 16,000 $m^3 d^{-1}$ (Table 2). In 2013, the filtration process in the water treatment plant was retrofitted with a filtration method using a ceramic membrane in the conventional method (e.g., sand filtration).

2.2. Field survey and data acquisition

Information on the operation of dam reservoirs, water treatment plants, TMP, and microalgae was obtained from the Geoje Region Management Office of the Korea Water Resources Corporation (K-water). Hydrometeorological data were obtained from the national water resources management information system operated by the Ministry of Land, Infrastructure, and Transport of Korea.

The basic water quality by water depth was measured after direct collection at 0.5 m intervals. The water temperature and dissolved oxygen were measured using a YSI-550 meter, pH was measured using an Orion-230A meter, conductivity was measured using a WTW Cond 3,100 m, turbidity was measured using a HACH 2,100 N meter (HACH Inc. Loveland, Colorado, U.S.), and transparency was investigated using a Secchi disc. The concentrations of chlorophyll-a (acetone method) and manganese (inductively coupled plasma-mass (ICP-mass) method) were analyzed according to Standard Methods [20].

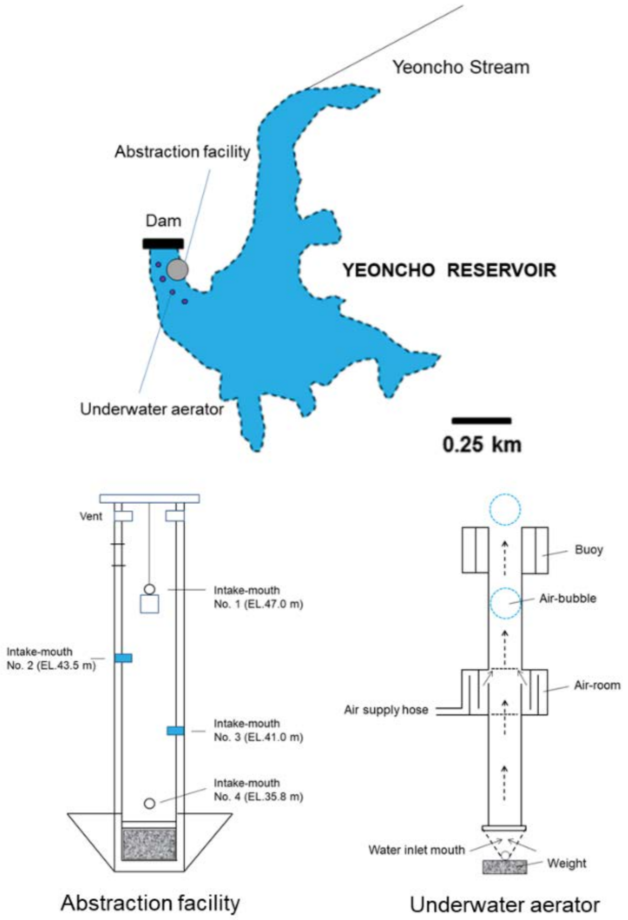

Fig. 2. Map showing the locations of the abstraction facility and the underwater aerators operating within the reservoir, and schematic diagrams explaining their detailed structures.

2.3. Statistical analysis

The descriptive statistics of the data and the Pearson correlation analyses between factors were analyzed using the SPSS version 18 statistical program (IBM-SPSS Inc., Armonk, New York, U.S.). The significance level was set at $p < 0.05$.

3. Results

3.1. Variation in the normalized TMP in the ceramic membrane filtration process

Fig. 3 shows the normalized TMP values continuously measured in four membrane filtration module lines installed at the Yeoncho water treatment plant from July 2014 to June 2017. The range of the normalized TMP values was 0.01–2.12 kg f cm^{-2}, and the average value was 0.61 kg f cm^{-2}. The change in the normalized TMP was very irregular, and the difference was severe between modules A and B–D (Fig. 3).

For the normalized TMP value, the frequency of exceeding 1.5 kg f cm^{-2}, which is the clean-in-place criterion, was common, and the width of the period was increased. Owing to the intensification of these problems, the water treatment

Table 2
General facilities and operation status of the Yeoncho water treatment plant

Attribute	Yeoncho water treatment plant
Water source	Yeoncho Reservoir
Facility capacity (m^3 d^{-1})	16,000
Facility component	Ozone + mixing/coagulation + MF + GAC
Membrane type	Ceramic MF (Metawater Co., Ltd., Tokyo, Japan)
Membrane modules	320 (4 series; 32 units)
Pre-treatment	Pre-chlorination, coagulants, and ozone
Filtration (h)	3.0
Physical cleaning (h)	2.0–2.5
Maintenance cleaning (times per week)	1–3
Chemically enhanced backwash	
Chemical cleaning (times per year)	2
Clean-in-place	

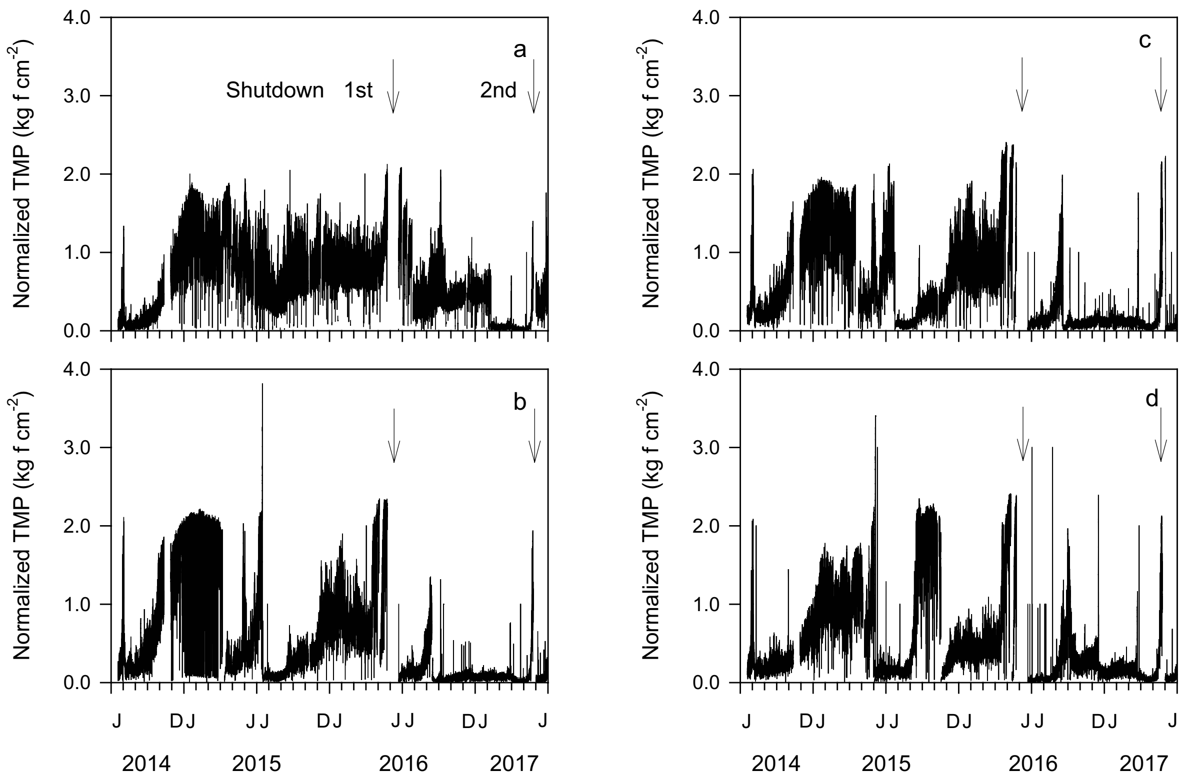

Fig. 3. Real-time fluctuations in the normalized transmembrane pressure (TMP) measured at 1 h intervals in the Yeoncho water treatment plant from July 2014 to June 2017. (a–d) represents the four membrane module lines.

plant was shut down for 28 and 6 d in 2016 and 2017, respectively, and the cause of the problem was only recently identified.

3.2. Daily variation in hydrological factors within the reservoir

Fig. 4 shows the daily fluctuations in the major hydrological factors observed in the Yeoncho Reservoir from January 2015 to April 2018. The range and average value of the inflow amount were 0.00–24.12 and 0.25 m^3 s^{-1}, respectively. The inflows were relatively high in October 2016 and early August 2017. The range and average value of the overflow were 0.10–11.17 and 0.69 m^3 s^{-1}, respectively. The overflow was high in 2016 when there was a high inflow, and although it was a short period, the maximum discharge was recorded in early July 2016. The water intake ranged from 0.00 to 0.44 m^3 s^{-1}, and the average value was 0.16 m^3 s^{-1}. Compared with that in other periods, it was quantitatively higher in July–September 2015 (0.11–0.23 m^3 s^{-1}) and relatively high in April 2016 (0.18 m^3 s^{-1}).

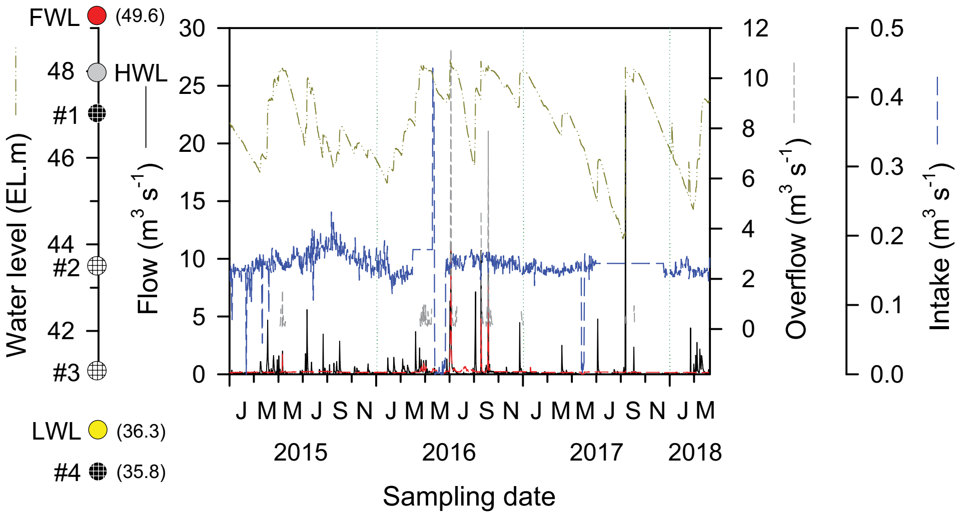

Fig. 4. Daily variation in the major hydrological factors of inflow, overflow (spillway discharge), intake, and water level in the Yeoncho Reservoir from January 2015 to April 2018. FWL: flood water level; HWL: high water level; LWL: low water level. #1–4 (EL. m): intake gate numbers in the selective withdrawal facility.

The water level in the reservoir varied in the range of EL. 44.13–48.28 m and the average value was EL. 46.76 m. The water level fluctuations were closely related to the inflows. The lowest water level was observed every year from January to February, but in 2017, it was in early September owing to prolonged drought. When the water level drops below EL. 47.0 m, the first intake mouth (No. 1) located at the top of the intake tower cannot be used.

3.3. Weekly variation in standing crops of freshwater microalgae

Fig. 5 shows the total cell density of freshwater algae and the distribution of standing crops of diatoms, cyanobacteria, and green algae observed in the Yeoncho Reservoir from January 2015 to December 2017. The range and average value of the total cell density were 204–10,829 cells mL^{-1} and 2,839 cells mL^{-1}, respectively. In terms of taxa, the range and average value of diatoms were 0–6,715 cells mL^{-1} and 1,889 cells mL^{-1}, respectively, those of cyanobacteria were 0–4,488 cells mL^{-1} and 375 cells mL^{-1}, respectively, and those of green algae were 0–2,771 cells mL^{-1} and 465 cells mL^{-1}, respectively. In the Yeoncho Reservoir, freshwater microalgae were abundant in February–March, June–July, and September–December. Only diatoms showed a high density of red tide levels (>5,000 cells mL^{-1}) between September and November of 2015 and 2017. Cyanobacteria, green algae, and flagellates did not show bloom levels (>15,000 cells mL^{-1}).

3.4. Opening and closing rates of the intake mouth and operation rate of underwater aeration

Fig. 6 shows the opening and closing rates of the water intake mouth and the operation rate of underwater aeration in the Yeoncho Reservoir from January 2013 to mid-May 2018. From January 2013 to June 2014, the opening rates of inlets No. 3 (EL. 41.0 m) and No. 4 (EL. 35.8 m) ranged from 80% and 55% to 100%, respectively, and thus, depended on the intake of lower water. From July 2014 to mid-April 2018, the opening rates of intakes No. 1 (EL. 47.0 m) and No. 2 (EL. 43.5 m) ranged from 50% to 100% and from 80% to 100%, respectively; hence, water in the upper layer was concentrated at the intake. Meanwhile, from August 2015 to June 2016, only 80% of intake mouth No. 3 was opened, while the other intake mouths were closed. From August 2017 to April 2018, water intake mouth Nos. 1 and 2 were opened by 70% and 80%, respectively, and water intake mouth No. 3 was opened 100%. Underwater aeration (<EL. 35.0 m) was operated at 100% from 2014 to 2017 every year from April to December.

4. Discussion

Generally, membrane fouling in water treatment is treated as an effect of pollution caused by natural organic substances, algae, and their by-products [21,22]. Therefore, the backwash method is also focused on this effect [23,24]. Previous research results have contributed to solving various problems related to membrane fouling by consistently presenting considerable physical and chemical achievements [25]. However, membrane fouling developed in the Yeoncho water treatment plant had a unique aspect. Even if the prior solutions for reversible and irreversible fouling were applied, there was no effect on the reduction in the TMP. Therefore, problem-solving in the water treatment process within the water treatment plant has limitations.

The water quality of the reservoir, which is a source of raw water as a water treatment plant, has a close relationship with the water treatment efficiency [16,19]. Therefore, it is inevitable that the water resource management of the reservoir must be treated as a priority. In the case of the Yeoncho Reservoir, the annual water level has fluctuated by approximately 4 m on average in recent years (Fig. 4). In particular, when the water level rises and

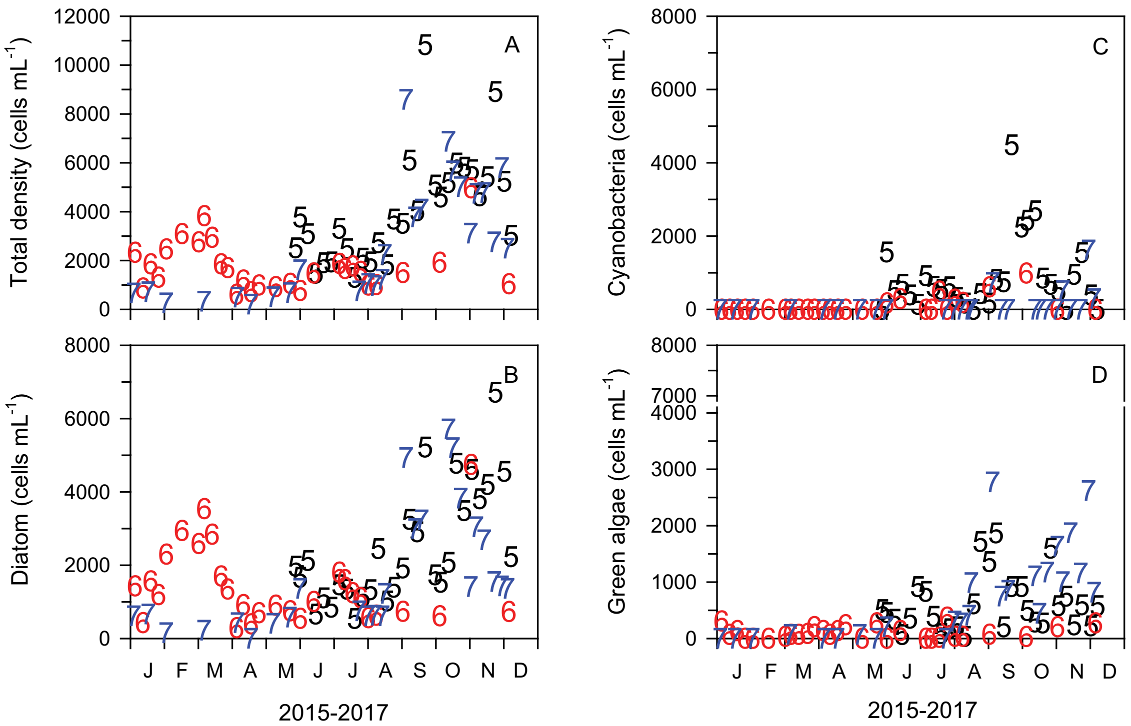

Fig. 5. Temporal distribution of total algae (A), diatoms (B), cyanobacteria (C), and green algae (D) densities were observed in the Yeoncho Reservoir from January 2015 to December 2017. The numeric symbols (5, 6, and 7) represent 2015, 2016, and 2017, respectively.

then falls, membrane fouling tends to occur, and it was found that the relationship was low with the amount of microalgae (Figs. 3 and 5). Looking at the fluctuations in the increase and decrease in the normalized TMP due to membrane fouling from 2014 to 2017, it was found that the repeated increase in the normalized TMP was the same as that when underwater aeration was artificially operated, and there was a highly positive correlation between them ($r = 0.980$; $p < 0.05$) (Fig. 6).

From the results of the investigation without underwater aeration in April 2018, turbidity increased rapidly at a depth of 12 m with a maximum of 108 NTU, and the chlorophyll-a concentration was 20.4 mg m^{-3}, which was 10 times higher than that of the surface layer (Fig. 7). Therefore, when underwater aeration disturbs the bottom sediment layer, the substances causing turbidity are transferred to the upper layer and diffuse to the entire layer. The re-suspended fine particles contained more than 90% clay with a size of less than 3.9 μm, which are seldom settled (1.214×10^{-7} m s^{-1}) [26,27]. These particles are directly supplied to the water treatment plant through the intake mouth and directly affect fouling. The analysis of fouling pellets accumulated in the ceramic membrane module revealed that organic matter fragments, microalgae, aluminum, manganese, and silica were the main components, and the total organic and inorganic contents were 48.5% and 51.5%, respectively. This result could be seen as a large proportion of the source material in the reservoir.

Fig. 8 explains the behavior of particulate matter that can induce membrane fouling in the Yeoncho Reservoir

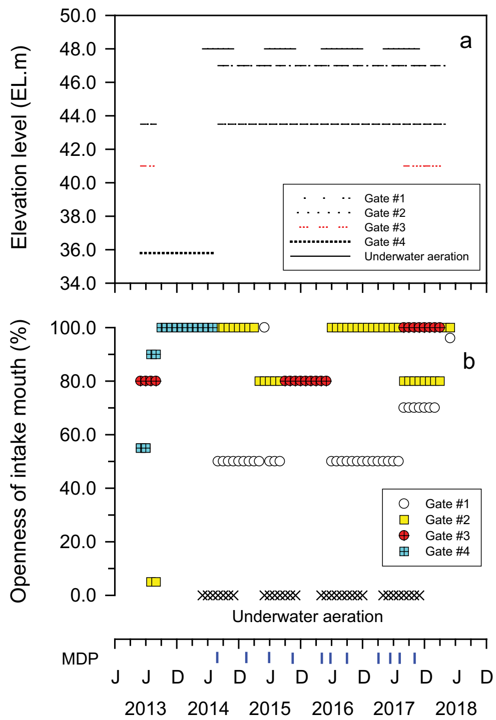

Fig. 6. Qualitative (a) and quantitative (b) results of the operation of the selective withdrawal facility and underwater aeration systems in the Yeoncho Reservoir from January 2013 to December 2018. Membrane differential pressure (MDP) refers to the time when the transmembrane pressure was severe.

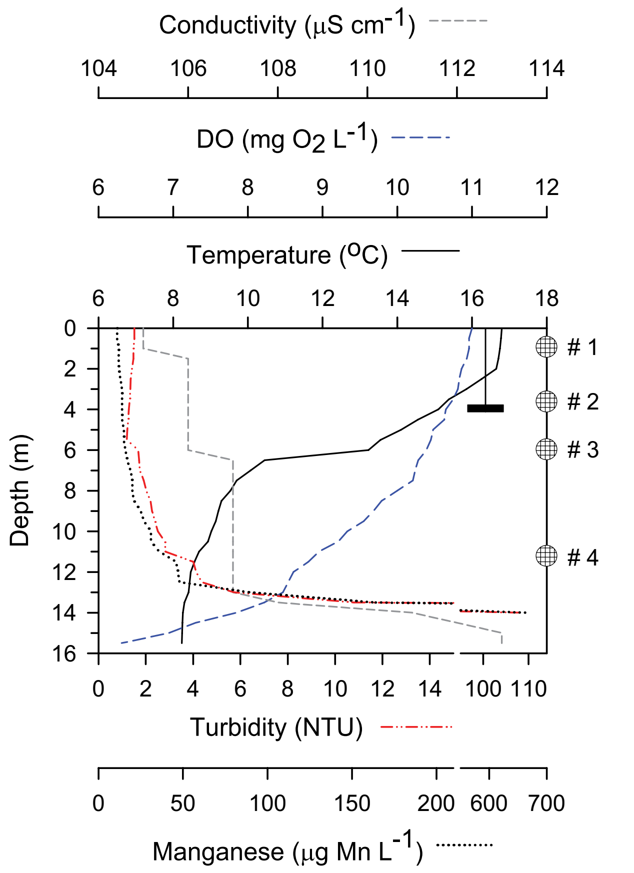

Fig. 7. Vertical distributions of major water quality factors were surveyed in the lower part of the Yeoncho Reservoir in April 2018. The horizontal black bar indicates the Secchi depth. #1–4: intake gate numbers of the selective withdrawal facility.

with a water intake structure linked to underwater aeration. Inflow water accompanied by rainfall generally has high turbidity. When stratified in the reservoir, a density flow is formed along with the depth of the water intake depending on the temperature, and pollutants are transferred to this layer [28–31]. At this time, the depth for selective intake could be an important consideration [19]. However, the water intake depth was variable or inconsistent in this study, and the water intake mouth was manipulated with the perception that the bottom water was usually clear. Moreover, although the lower layer close to the sediment had higher turbidity than the upper layer, the water body was dynamically enriched with suspended fine particles owing to underwater aeration throughout the year.

As a result, underwater aeration may increase the difficulty associated with water treatment in water treatment plants that receive and supply this water. Therefore, when investigating the cause of membrane fouling in a water treatment plant, it is necessary to comprehensively examine the actual conditions in the reservoir and the dynamics of the foulants. Additionally, in order to effectively reduce or control membrane fouling during the filtration process, it is necessary to first minimize the artificial disturbance of the water body in the reservoir.

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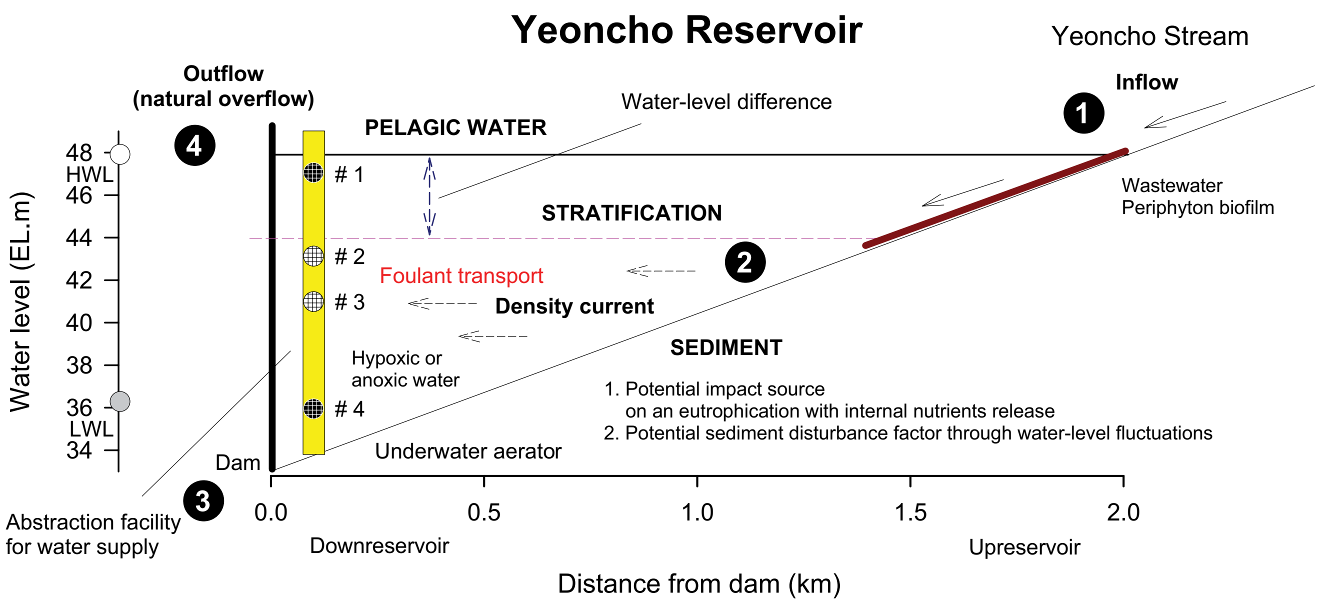

Fig. 8. Schematic diagram explaining the relationship between foulant transport from the Yeoncho Reservoir to the Yeoncho water treatment plant and the abstraction facility and underwater aerators. HWL: high water level; LWL: low water level. #1–4: intake gate numbers of the selective withdrawal facility.

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