Problematic algae in the sedimentation and filtration process of water treatment plants

Gyeongje Joh, Yang Soon Choi, Jae-Ki Shin and Jiyoung Lee

ABSTRACT

Problematic algae, species that do not settle or are not easily removed by water treatment processes, are common in many water treatment plants (WTPs). We recorded algae in the water that overflowed from sedimentation basins (SBs) to filtration basins of WTPs in South Korea. Diatoms were common and other algae were not discernible in the flocs. Our field observation indicated that long and needle-shaped algae were less likely to settle and more likely to be present in overflow water. Many diatom cells or colonies that were extremely deformed from spherical had high overflow rates. Another long alga, *Phormidium* sp. (Cyanobacteria), originated from periphytic biofilms attached to SB walls. Algae that form long cells or colonies are less compact and less likely to settle as poor flocs. Species that overflowed the basin also clogged the sand filters, leading to a need for repeated backwashing, thus limiting the production of clean water. Species that clogged the sand filters included the needle-shaped diatom *Synedra acus* and the discoid diatom *Stephanodiscus hantzschii* f. *tenuis*. We also observed two cases where *S. acus* clogged WTP filters, requiring frequent backwashing that resulted in reduced production of drinking water and economic loss.

Key words | algal shape and size, problematic algae, sedimentation and filtration, water treatment plant

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INTRODUCTION

The drinking water of many cities in South Korea comes from the main channels of river systems. To supply this water, engineers have constructed many river-like lakes by installing dykes in the main channel. The estuaries of some large rivers have been embanked to support water demand. These measures are necessary so that water is available during the dry season for drinking, irrigation and industrial processes. Unfortunately, the source water is contaminated by large levels of municipal and industrial pollutants from the watershed, resulting in substantial algal blooms that threaten water quality (Yu *et al.* 2001).

Control of algal growth during the water treatment process has received increasing attention owing to the persistent eutrophication of freshwater in Korea. In particular, an overabundance of algae and algal metabolite increases coagulant demands, shortens filter runs because of clogging, increases the need for chlorine and the need to manage disinfection by-products, produces unpleasant tastes, odors and toxins, and increases microbial regrowth potential in the distribution systems (Knappe *et al.* 2004; Gray 2008). The main cause of inefficient algal removal is poor flocculation, which is determined by species mobility (Petruševski 1996). Furthermore, the presence of algae in the source water leads to the release of undesirable metabolites during the water treatment process (Her *et al.* 2004). Conventional treatment processes cannot completely remove algae and algal by-products, so the presence of algae needs to be minimized (Mouchet & Bonnélye 1998; Henderson *et al.* 2008). The presence of algae can also lead to high concentrations of soluble or biodegradable organic compounds. Following chlorination, these organic compounds can be a source of trihalomethanes (Hoehn *et al.* 1980).

Algae have highly variable morphologies and other factors related to the ease with which they can be removed

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from water treatment plants (WTPs) (Walsby & Xypolyta 1977; Choi *et al*. 2006). In particular, spheroidal algae settle more rapidly than non-spheroidal algae (Walsby & Xypolyta 1977; Choi *et al*. 2006).

Many WTPs in South Korea use coagulants to effectively remove algae (Park & Lee 2000; Jun *et al*. 2001; Lee *et al*. 2001; Kim *et al*. 2002). In addition, pre-oxidation treatments, such as pre-chlorination, pre-ozonation and potassium permanganate, are often to manage algal problems (Lee *et al*. 2001; Chen & Yeh 2005; Henderson *et al*. 2008). Various filtration systems are also used to remove algae (Yun *et al*. 2002). Despite all these efforts, algae remain a fundamental problem for WTPs. Biological approaches for managing algal problems have not been implemented owing to the lack of basic biological information about the contaminating species. Problems with algal growth in WTPs are common throughout the world, including in the Biesbosch reservoir in the Netherlands (Petruševski 1996), WTPs in France and Germany (Mouchet & Bonnélye 1998), the Thames River in the UK (Bowles & Quennell 1971), and facilities in the United States (Jayangoudar & Ganapati 1965), Japan and Taiwan (Chen & Yeh 2005).

In this study, we made field observations of problematic algae and their flocs in the coagulation and sedimentation process at 29 WTPs in South Korea. We also studied morphological and other characteristics of algae present in the water that overflowed from sedimentation basins (SBs) to filtration basins (FBs). Finally, we examined two cases in which algae were responsible for filter clogging and assessed the subsequent economic losses of these events.

MATERIALS AND METHODS

Investigation of problematic algae

Investigations were conducted at 29 WTPs in South Korea from September to December 2001. The WTPs were operated and managed by the Korea Water Resource Corporation (KOWACO) and their treatment capacity ranged from 10,000 m^3/day to 786,000 m^3/day. These plants used basic or conventional treatment processes, such as sedimentation, use of a gauging well, coagulation and flocculation, and sand filtration. Most plants were equipped with rapid sand filters (RSFs) and used pre-chlorination before coagulation. In addition to the KOWACO plants, samples were also collected from two WTPs located in the lower parts of the Nakdong River (D plant) and Lake Paldang of the Han River (G plant), the two largest rivers in Korea. These plants have the potential to produce 1,500,000 m^3/day and 110,000 m^3/day, for D and G plants, respectively. The D plant has a sedimentation system that uses a pulsator clarifier, namely floc-blanket sedimentation, and advanced treatments by ozonation and granular-activated carbons (GACs). The G plant has typical and conventional facilities for coagulation and sedimentation, and dual-media filters composed of anthracite with 50 cm depth in the upper layer and sand with 25 cm depth in the lower layer. The G plant and 29 KOWACO plants have used PAC (polyaluminum chloride, typically 10.5 mg/L) which has been the most common coagulant in South Korea for a long time. On the other hand, the D plant adopted polysulfate organic magnesium as the primary coagulant and has occasionally used PAC. Though the performance of the coagulant depends on the concentration of Al_2O_3, PAC is known to be most effective in improving the effluent quality of algae-rich water (KOWACO 1999).

Algal samples were collected from the raw water or gauging well, SB, effluent of sand filters, and backwash return water in the plant. In the water treatment process, water overflowing from SBs to FBs and the effluent water of FBs were sampled to observe the algae and diatom shells. Algae were observed under a microscope (Zeiss model Axioplan, Göttingen, Germany) at 400× magnification. Algal cells were counted using a Sedgwick-Rafter chamber (1.0 mL volume). Cell abundances of each species were measured, the overflow (%) was determined as the cell-count ratios of overflowing water to raw water, and overflow frequency of each species was determined based on the numbers of overflow. Removal accounted for the settling or disappearance of algae in SBs relative to the raw water. In the G plant, which has eight sand filters, the daily frequency of backwash was recorded and water backwash volumes were also calculated.

Settling of two diatom species

Two test species, *Synedra acus* and *Stephanodiscus hantzschii* f. *tenuis*, were isolated from the Nakdong River by capillary pipette techniques (Guillard 1973). Clonal and unialgal cultures were maintained in a controlled room with a photosynthetically active radiation of 100–120 μmol/m^2 s (14 h light, 10 h dark cycles). Diatoms were incubated in DM media (Beakes *et al.* 1988). When diatoms were in the log growth-phase, they were thoroughly mixed with PAC coagulants (80 mg/L) in a programmable Jar Tester (model PB-900, Phipps & Bird, Richmond, VA) for settling measurement. Agitation conditions in the jar were 120 rpm of rapid mixing for 2 min, 60 rpm of slow mixing for 18 min, and subsequent settling time was 30 min.

We measured the settling rates of cultured diatoms using the settling column method (SETCOL) developed by Bienfang (1981). This apparatus has six acryl columns (25 cm high, 4 cm diameter) and three sampling ports (H_1: top, H_2: middle and H_3: bottom). The initial algal concentration was determined by filling the column with algal floc and allowing it to stand for a defined period of time. After the supernatant water was siphoned from the column, the remaining water up to H_3 level (3.4 cm from the bottom) was thoroughly mixed and cell counts were measured under a microscope. The removal and the settling velocities were determined from measurements made over 3 h. These experiments were conducted in a dark room at 20 °C. All algae were exposed to NaOCl (the final concentration of 1.5 mg Cl/L available chloride 7%) prior to the settling experiments.

RESULTS

Abundance of algae in raw water

Figure 1 shows the chlorophyll-*a* concentration of planktonic algae and turbidity of the raw water of the Nakdong River. The algal blooms during the dry season lasted for five months (November to March). The peak concentration of chlorophyll-*a* (>200 μg/L) was detected in late February and early March. During the period of rapid algal increase, small centric diatoms, *Stephanodiscus hantzschii* f. *tenuis* and related species appeared in monospecific blooms, with an abundance of 14,500–62,700 cells/mL. The increase in diatom levels gave the water a yellow-brown color. As shown in Figure 1, high algal biomass scarcely had an effect on nephelometric turbidity unit (NTU) turbidity values, implying that turbidity and chlorophyll-*a* are indicators of different water properties.

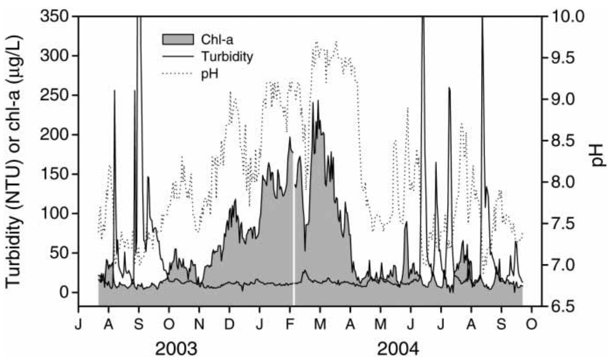

Figure 1 | Turbidity (NTU), chl-*a* concentration and pH of raw water in the lower parts of the Nakdong River (data from http://water.busan.go.kr/purity/statistics1.do, Busan Water Authority, South Korea, accessed 4 March 2011).

In contrast to the dry season, the river had fluctuating discharges and water levels from July to September, during which period there were intense rainfalls. At these times, water flows were variable to a great extent and the suspended materials markedly increased the turbidity. High turbidity levels did not allow for normal treatment of the drinking water during this period.

Removal of algae from overflow water versus raw water

To determine the removal rates of algae in WTPs, which have diverse water sources including lakes, rivers and estuarine lakes, we counted algal cells or colonies in the raw water and the water that overflowed from SBs to FBs. All removal efficiencies were relatively low at WTPs in rivers and downstream lakes (e.g. Lake Paldang and Asan), whereas they were high in the upstream lakes (e.g. Lake Yongdam and Unmum) and small-scale lakes (e.g. Lake Boryeong, Buan, Sueo, Hwangji) (Table 1). When algal numbers were greater than 10,000 cells/mL in the raw water, the mean removal rate of algae was 92%, greater than the overall average. Regardless of different efficiencies of algae removal, the residual algal abundance in the overflow water from SBs could be as great as 4,300 cells/mL. The Cheongju WTP was unusual in that the numbers of algae in the overflow water were greater than those in the raw water because of resuspension of algae that detached from the basin wall. The basin of this WTP is occasionally contaminated with the settled debris and biofilm on the walls.

Table 1 | Removal of algae by SBs, and comparison of cell counts of raw water and SB overflow water in November 2002

No.	Name of WTP	Water source	Treatment capacity ($\times 10^3$ m^3/day)	Cell counts (/mL) Raw water	Overflow from SBs	Removal rate (%)
1	Chungju	Han R.	250	1,900	0	100.0
2	Ilsan	Han R.	250	2,890	103	96.4
3	Deokso	Han R.	200	2,255	221	90.2
4	Suji	Paldang L.	711	3,998	675	83.1
5	Banyeol	Paldang L.	190	5,095	1,385	72.8
6	Siheung	Paldang L.	258	10,602	223	97.9
7	Seongnam	Paldang L.	786	3,929	260	93.4
8	Wabu	Paldang L.	215	4,110	945	77.0
9	Seoksong	Geum R.	300	40,175	3,614	91.0
10	Gunsan	Geum R.	130	3,543	1,620	54.3
11	Asan	Asan L.	350	2,330	1,604	31.2
12	Sanseong	Dongjin R.	90	5,665	1,625	71.3
13	Daebul	Yeongsan R.	115	23,108	4,300	81.4
14	Gumi	Nakdong R.	400	800	25	96.9
15	Bansong	Nakdong R.	120	16,899	315	98.1
16	Hakya	Hyeongsan R.	62	638	70	89.0
17	Onsan	Taehwa R.	320	24,015	3,520	85.3
18	Cheongju	Daecheong L.	290	7,055	33,102[a]	00.0
19	Boryeong	Boryeong L.	285	1,960	15	99.2
20	Gosan	Yongdam L.	150	3,070	10	99.7
21	Buan	Buan L.	87	4,555	35	99.2
22	Hwasun	Juam L.	100	910	10	98.9
23	Byeolrang	Sueo L.	45	1,547	7	99.5
24	Unmun	Unmun L.	10	2,045	65	96.8
25	Jain	Unmun L.	40	2,270	120	94.7
26	Sacheon	Jinyang L.	121	11,127	310	97.2
27	Yeoncho	Yeoncho L.	16	19,327	1,740	91.0
28	Gucheon	Gucheon L.	20	2,350	105	95.5
29	Hwangji	Gwangdong L.	70	260	0	100.0
	Average			7,192	819	88.6

These conventional treatment plants are managed by KOWACO.
R, River; L, Lake.
[a]Number excluded for calculation of an average value.

Figure 2(a) shows the number of each algal species in the overflow for all 29 WTPs. We observed 16 species or algal groups in the SB overflow water, with considerable differences in the counts of each species. Most species had an overflow rate of less than 10%. But the algal species with more than 10% overflow were *Phormidium* filaments (mainly *Phormidium tenue* and partly *Oscillatoria* species) of the Cyanobacteria, and *Nitzschia acicularis*, *Synedra acus*, *Aulacoseira granulata* var. *angustissima* and *A. subarctica* of the Diatomophyceae, which were most resistant to settling in basins. The most problematic cyanobacterium was *P. tenue* and its related groups. As a result, despite the

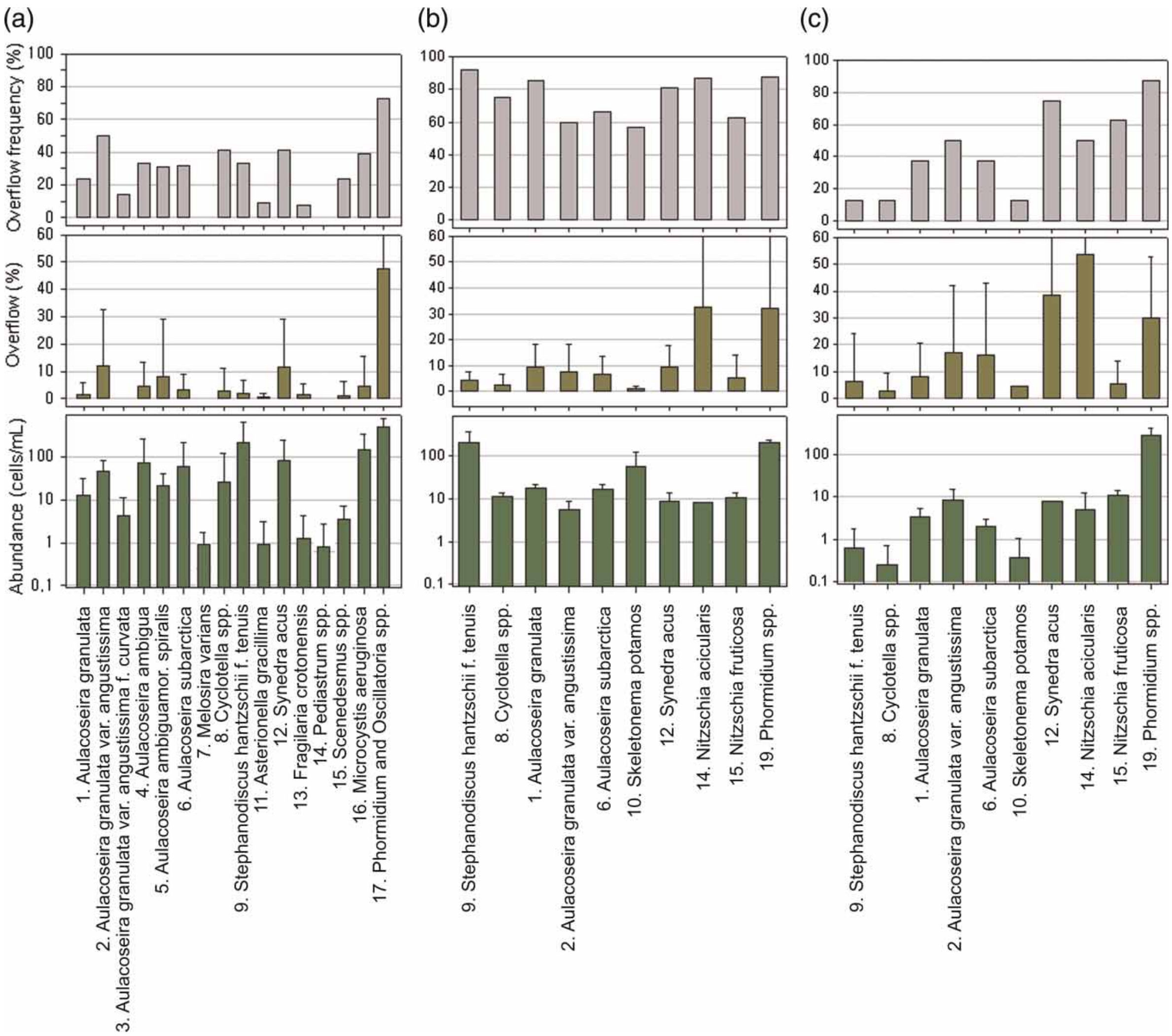

Figure 2 | Algal overflows from SBs to FBs at all 29 WTPs (a) and D WTP (b and c). Data show frequency of species overflow relative to the numbers of overflow (top), cell overflow of each species relative to raw water (middle), and cell abundance of algal species in raw water (bottom), from September 2002 (a), April 2003 (b), from May to September 2003 (c).

formation of algal flocs in the process of coagulation and flocculation, significant amounts of algae remained in the overlying basin water.

On the other hand, colonial species such as *Asterionella formosa* and *Fragilaria crotonensis* were effectively removed by the water treatment process. Moreover, although *Melosira varians* (Diatomophyceae) and *Pediastrum* spp. (Chlorophyta) occurred in significant abundance in raw water, they were completely removed during the course of water treatment (Figure 2(a)). The overflow frequency of each species is the percentage with at least one algal cell in the overflow water. As a result, species with high overflow rates had high frequencies in the overflow.

Algal overflows in a WTP (D plant) near the Nakdong River were monitored weekly. There were 10 major species or groups in the SB (Figures 2(b) and (c)). The overflow rates of *Phormidium* cells averaged 30%, and algal cells in the overflow water occasionally exceeded those of the raw water. In some cases, the *Phormidium* numbers in the SB water were 3–10 times greater than those of the raw water. An overestimation of *Phormidium* filaments was due to the autogenic growth of these species on the cement walls of the basins. Except for *Phormidium*, the algae in the overflow water were all diatom cell skeletons. The highly overflowing species from SBs were *Nitzschia acicularis*, *Synedra acus*, *Aulacoseira granulata* var. *angustissima* and

A. granulata, which are needle or long filament shaped, implying settling resistance in the sedimentation process (Figures 2(b) and (c)). The residual concentrations of *Phormidium* and *Stephanodiscus* in the overflow water were higher than those of any other species. Based on many observations, *Synedra acus* had a relatively high overflow rate despite its low concentration in the raw water. However, all *Synedra acus* was completely removed by sand filtration, whereas *Stephanodiscus* deep penetrated the sand filter so that some cells were in the effluent water of FBs.

Many filaments and colonies of algae in the overflow water were different from those of the raw water. Though many algae were in the form of long filaments in the raw water, they were separated into unicell or assemblages of a few cells through the water treatment process. It was observed in our experiments that the unicell or individual alga was more reluctant to settle in the basin than the colony of algae.

Flow obstruction by *Synedra acus*

Figure 3 shows cell counts of *Synedra acus* in raw water, the water overlying in the basins, and the corresponding frequencies of backwashes in the G WTP. Between October 1997 and June 1998, there were three peaks of *Synedra* in raw water, with maxima 616, 397 and 1,026 cells/mL. Unlike other diatom groups, a low density of this species (<1,000 cells per mL) led to serious filtration obstruction. Overflow of this species from raw water to the filtration system ranged from 15 to 81% (mean 50%, $N = 31$). These diatoms in the overflowing water were completely trapped on the RSF as a result of their long-needle shapes, and clogged the sand filters. The lifetime of the RSFs was considerably shortened, and backwash frequency increased to a maximum of 47 times per day (total eight basins, equivalent to 5.9 times per basin per day). This is 15 times the normal rate. During these events, water production is

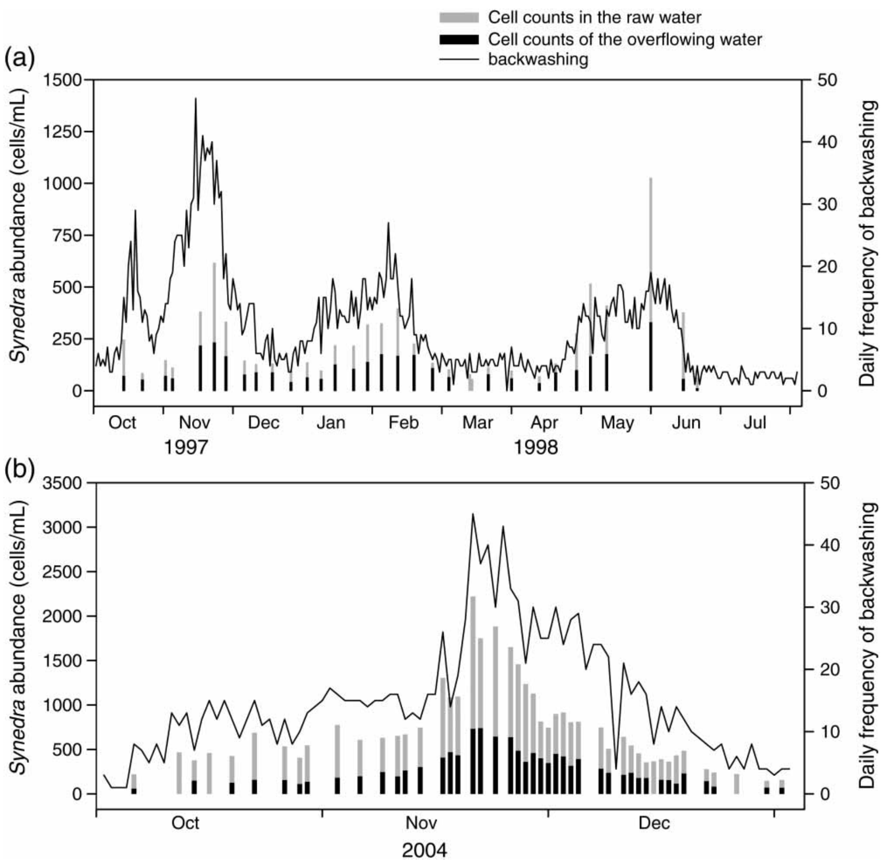

Figure 3 | Abundance of *Synedra acus* in raw water and in the overlying water of the basins, and daily backwash frequencies of eight sand beds during the *Synedra* blooms in the G plant on the Han River.

significantly reduced. In addition to *Synedra acus*, *Aulacoseira* species, *Fragilaria crotonensis* and *Asterionella formosa* and other algae in raw water were almost removed by settling in the SBs and their overflows were less than 5% suggesting a negligible effect on the anthracite clogging.

Figure 3(b) shows a second *Synedra* event in 2004. In this case, *Synedra* abundance ranged from 145 to 2,219 cells/mL (mean 729 cells/mL) and overflow ranged from 22 to 51% (mean 38%, $N = 43$). The daily backwashes ranged from 1 to 45 (average 14.9). The backwash frequency suddenly increased above the 200 cells/mL concentration in the first event of 1997 and the 500 cells/mL in the second event of 2004. About 95% of *Synedra* shells accumulated in the upper 1 cm of the anthracite layer and did not penetrate to the basin. Clogging of the sand filter greatly reduced water production because of the frequent backwashing and the need to discard backwash water.

Filamentous or cylindrical, and needle-shaped cells in the overflowing water from SBs were almost removed through the filtration systems, while some discoid and small centric diatoms passed through sand filters. Penetration of small discoid diatoms (10–14 μm in diameter) through the RSFs was observed during the *Stephanodiscus* blooms in February when the concentration of discoid diatoms ranged from 6,000 to 94,100 cells/mL. The removal of diatoms *Stephanodiscus* or *Cyclotella* by sand filters ranged from 0.10 to 0.18% and the cell concentration from 10 to 200 cells/mL.

DISCUSSION

In water treatment, the sedimentation and filtration stages are the most important for removal of the algae and particulates from raw water. The efficiency of algae and particulate removal depends on the quality of the raw water and on the procedures used by the WTPs (Table 1 and Figure 2). Consequently, significant numbers of algal cells can overflow the SB into the FB. In our study, we found that significant levels of algae were removed during the filtration stage, so that backwashes had to be performed more frequently. We found that the raw water of the WTPs was mostly occupied by diatoms, to a lesser extent by chlorophytes, and the shape and size of algae are important in the settling and filtering process of water treatment.

Filter-clogging algae

Based on our observations, algae can cause three types of filter clogging problem. First, slender or needle-shaped diatoms such as *Synedra acus*, *Nitzschia acicularis* and *Asterionella formosa* can attach to many flocs, reducing their density so they overflow the SB. Second, despite the more effective flocculation, significant amounts of discoid diatom *Stephanodiscus* are transferred to the RSF effluent owing to high concentrations in the raw water. Additionally, coagulant flocs with mucilaginous algae (such as cyanobacteria and *Microcystis* etc.) with low density tend to float to the surface and overflow the SB and then clog the filter. Problems caused by *Microcystis* frequently occurred in the summer after intense rainfalls.

Synedra acus and *Stephanodiscus hantzschii* f. *tenuis* have been reported as the most troublesome species (Jun *et al.* 2001; Choi 2002; Cho *et al.* 2006). *Stephanodiscus*, a discoid diatom, does not readily settle because of its small size, and is responsible for the high turbidity of basin effluents and an unpleasant water odor (Cho *et al.* 2006). *Stephanodiscus* can penetrate deep into the filter bed and thereby prevent effective water filtration (Bowles & Quennell 1971). *S. acus*, at approximately 200–300 cells per mL in raw water, can also cause serious problems by clogging sand filters, making it necessary to perform more frequent backwashes (Siheung WTP 1996; Jun *et al.* 2001; Choi 2002, 2008). From 1995 to 2002, in the six important WTPs located below Lake Paldang, water treatment was placed in a state of emergency for an average of 5–24 days owing to blooms of *Stephanodiscus* and for an average of 7–16 days owing to blooms of *Synedra* (Cho & Cho 2005). The filtering efficiency in the previous WTPs was inhibited when the cell counts in raw water are about 200 cells/mL of *Synedra* or 20,000 cells/mL of *Stephanodiscus*.

Table 2 summarizes our review of sedimentation and filtration processes used at WTPs in Korea. Approximately 30 species or algal groups were reported as troublesome, and diatoms such as *Stephanodiscus*, *Aulacoseira*, *Fragilaria* and *Synedra* were the most troublesome. *Stephanodiscus*, *Nitzschia*, *Synedra*, *Scenedesmus*, *Euglena* and *Phacus* have also been observed in the effluent water of pilot-scale sand filters (Ryoo *et al.* 1994). Very thin or membrane-shaped

Table 2 | Problematic species of algae in water clarification (mainly SB and filtration) in Korea

Algal group	Algal species	SB	FB	Cited reference[a]
Cyanobacteria	*Microcystis aeruginosa*	++		2, 4, 6
	Microcystis spp.	++		2, 5
	Coelasphaerium species	++		2
	Palmella spp.	+		2
	Oscillatoria minima	++		6
	Oscillatoria spp.	++		5, 6
	Phormidium spp.	++		6
	Anabaena spiroides	++		6
	Anabaena spp.	++		5, 6
	Aphanizomenon spp.			6
Diatom	*Stephanodiscus hantzschii* f. *tenuis*	+++	+++	1, 2, 4, 5, 6
	Cyclotella meneghiniana	+		6
	Aulacoseira granulata and its relatives	+	+	1, 2, 4, 5, 6
	Asterionella formosa	++	++	1, 2, 6
	Fragilaria crotonensis	+		1, 2, 4, 5, 6
	Tabellaria flocculosa	+		2
	Synedra acus	+++	++	1, 2, 4, 5, 6
	Navicula spp.	++	+	1
	Nitzschia acicularis	++	++	1
Chlorophyte	*Coelastrum* spp.	+	+	1
	Chlamydomonas spp.	+		3
	Ankistrodesmus falcatus	++	++	1, 6
	Actinastrum hantzschii f. *fluviatile*	+		6
	Scenedesmus spp.	+++	+++	1, 6
	Pediastrum spp.	+		1
	Staurastrum sp.	+		3
Euglenoid	*Euglena* spp.	++	+	1, 6
Dinoflagellate	*Peridinium* spp.	++		5
Cryptomonad	*Rhodomonas* spp.	+		6
	Cryptomonas spp.	+		6

The extent of the problem was graded: +++, severe; ++, common; +, rare.
[a]1, Ryoo *et al*. (1994); 2, Siheung WTP (1996); 3, Chung *et al*. (1998); 4, Cho *et al*. (2006); 5, KOWACO (1999); 6, this study.

algae (*Euglena* and *Phacus*) can also penetrate sand filters as a result of their high elasticity.

Similar problems have occurred throughout the world: for example, in the Thames River in the UK in 1969 (Bowles & Quennell 1971), the Rhine and the Meuse Rivers in the Netherlands (Vlaški *et al*. 1996), many WTPs in France and Germany (Mouchet & Bonnélye 1998), and elsewhere (Jayangoudar & Ganapati 1965). Palmer (1980) has compiled a list of 45 significant filter-clogging algae found in the UK.

Economic loss due to frequent backwashes

Backwash water ordinarily returns to the gauging well to join the raw water, but must be discarded if there is a high concentration of empty diatom cells and other debris, thus decreasing water production. Table 3 summarizes our case study of backwash water at the G WTP. For 71 days (5 October to 31 December 2004), there was a loss of about 770,000 m^3 of water owing to high concentrations of diatom shells and other debris. The daily loss (10,900 m^3) corresponds to 18% of the daily volume (60,000 m^3) of treated water. This resulted in a significant economic loss and deterioration of water quality.

The occurrence of diatom *Synedra* and *Stephanodiscus*

The abundance of *S. acus* has been reported to be less than a few thousand cells per mL in Korean freshwater (Lee & Jung 2004)

Table 3 | Water loss due to discard of backwash water or without reuse during the second *Synedra* algal bloom of the G plant (treatment capacity 60,000 m^3/day) in 2004

Interval	Days	Abundance in raw water (/mL)	Daily water loss (m^3/day)	Daily frequency of backwashes
5–15 October	11	<500	8,530	9.5
16–31 October	16	500–700	10,090	12.2
1–15 November	15	600–800	10,910	15.5
16–30 November	15	800–2,200	12,260	30.1
1–14 December	14	350–900	11,030	19.1
15–31 December	17	150–400	800	7.0
Sum	71	–	770,840	–

and is known to bloom more frequently in lakes than rivers. This species is one of the ten most dominant phytoplanktons in the lower parts of the Han River and before the 1990s it was the most common phytoplankton in the Han River (Lee & Jung 2004; Kwon *et al.* 2006). In the Nakdong River, *S. acus* usually occurs at 10–100 cells/mL in spring (April to July) and autumn (September to November), and peaks at 200–500 cells/mL in autumn (unpublished data). A poll of Korean WTPs indicated that *S. acus* was among the most problematic algae (KOWACO 1999).

However, the *Stephanodiscus* diatom group also causes problems. *S. hantzschii* f. *tenuis* blooms in most rivers in Korea during the cold season (October to April) (Cho *et al.* 2006) and the abundance of *Stephanodiscus* diatoms can reach ranged 5,000–120,000 cells/mL. This species is a small discoid (10–15 μm diameter), so blooms can significantly reduce the coagulation and sedimentation efficiencies of the water treatment process. Even if diatom removal is relatively efficient, significant numbers of *Stephanodiscus* can overflow the SB. Furthermore, because of its small size, this species can penetrate the sand filters with concentrations of 1–10 cells/mL in the filter effluent.

Diatoms are known to inhibit the performance of the sand filters of WTPs throughout the world (Palmer 1962; Jayangoudar & Ganapati 1965; Bowles & Quennell 1971; Hutchinson & Foley 1974; Konno *et al.* 1994; Jun *et al.* 2001; Cho & Cho 2005). In particular, *Synedra* problems have been frequently reported since the 1960s (Jayangoudar & Ganapati 1965).

The shapes of problematic algae

Algae floating in the SB water and those transferred to the FB were primarily diatoms. Diatom shells are composed of silica, so can be easily identified. Other algae are degraded or aggregate into flocs, making identification difficult. In addition to diatoms, we also observed the cyanobacteria *Phormidium tenue* (and relatives) and *Oscillatoria* sp. *Phormidium* filaments were not embedded in aggregated flocs and separated from suspended floc assemblages to float independently. Most *Phormidium* filaments originated from biofilms on the SB walls. As *P. tenue* filaments are relatively short, they can be separated from algal clumps. However, the long filaments of *Oscillatoria splendida*, *O. amoena* and *Phormidium autumnale* were entangled in masses of biofilm, and unialgal filaments were rare.

Long and slender-shaped algae (such as *Synedra acus*, *Nitzschia acicularis*, *N. fruticosa*, *Aulacoseira granulata* and their relatives) were less likely to settle in SBs and were more likely to overflow into FBs (Choi *et al.* 2006). The settling velocity was also related to the algal morphological characteristics, and the long and thin algae had low velocity (Walsby & Xypolyta 1977). When algae form flocs with other particles or organic matter, the resulting floc is less dense and less likely to settle. It has been previously noted that the efficiency of algal removal in the SBs of WTPs is related to the size and shape of algal cells or colonies (AWWARF 2002).

Algal problems and control strategies for WTPs

According to a survey, WTP algal problems mainly occur in April–May and September–November in lake water, and in summer and winter in river waters (KOWACO 1999). The problems caused by algal blooms include: reduced filtration duration, poor coagulation, ineffective sedimentation, and offensive taste and odor. Most WTPs in South Korea can minimize the impact of algal blooms by temporarily blocking the water intakes or using selective intakes from deep beneath the surface, where algal concentrations are low. To overcome the problems associated with algal blooms, the WTPs commonly use pre-chlorination (48%), increased coagulant doses (24%), PAC treatment (16%) and regularly change coagulants (4%) (KOWACO 1999). However, these measures were only effective for 17% of total plants.

Treatment protocols depend on the turbidity and chlorophyll-*a* level of the raw water (Janssen & Buekens 1993). Though chemical application performs reasonably well with information based on the turbidity of raw water, the treatments considered can be misleading because of interference by the algae. During algal blooms, serious operational difficulties can occur during the coagulation and flocculation processes. Thus, coagulant or disinfectant use may be necessary.

In our case study of the G WTP (Figure 3(a)), the first peak of *Synedra* (in 1997) was associated with the need to regularly backwash the filter. After the first series of backwashes, three modifications were performed in the flocculation and filtration process (Choi 2008). In the first bloom, these modifications to the two processes changed the coagulant so that it was better distributed. Furthermore, as fine particles or other matter clogged the pores of the anthracite media of the column, the filter was removed for anthracite media skimming. These complementary measures improved filter performance so that less frequent backwashes were needed. Compared with the 1997 algal bloom, the removal efficiency of the third *Synedra* bloom was 17% better during sedimentation and 95% better during filtration (Choi 2008).

The first task when resolving an algal problem is to control algae in the source waters, using chemical, physical or biological approaches (Izaguirre & Devall 1995). Additional pre-treatment strategies could be used before the coagulation and flocculation processes. Killing algae by pre-oxidation (pre-chlorination, ozonation, potassium permanganate) is often effective (Duguet *et al.* 1995; AWWARF 2002; Henderson *et al.* 2008). In addition to the use of coagulants and pre-oxidation, filtration systems can also be effective tools to remove the algae in water treatment processes (Yu *et al.* 1990; Petruševski 1996). Regardless of traditional usage of pre-chlorination, the settling removal of two important diatoms, *Synedra* and *Stephanodiscus*, were significantly reduced after the pre-chlorination, compared with the untreated algae (Figure 4). With chlorination treatment, siliceous diatom cells lose cellular materials giving them a lower density.

In our study, conventional treatment processes did not completely resolve algal problems in WTPs. In conventional WTPs, sedimentation is an intermediate sink and sand filtration is a final barrier for the removal of impurities and algae. Consequently, additional strategies are required to improve the water treatment. In the 1960s, the microstrainer was the first instrument to directly remove algae (AWWA 1995). However, algae removal by the microstrainer varies greatly depending on the species, and removal rates are particularly poor for small species (Mouchet & Bonnélye 1998).

Dissolved-air flotation (DAF) can effectively remove algae from wastewaters and other waters (Ezwald & Wingler 1990; AWWARF 2002; Henderson *et al.* 2008), and such facilities have become more common in Europe during the past 30 years (AWWARF 2002). In Korea, DAF facilities are considered an alternative to sedimentation and have been in operation at two KOWACO WTPs (Shin 2002). However, the high cost of these facilities has prevented the widespread adoption of DAF or microstrainers

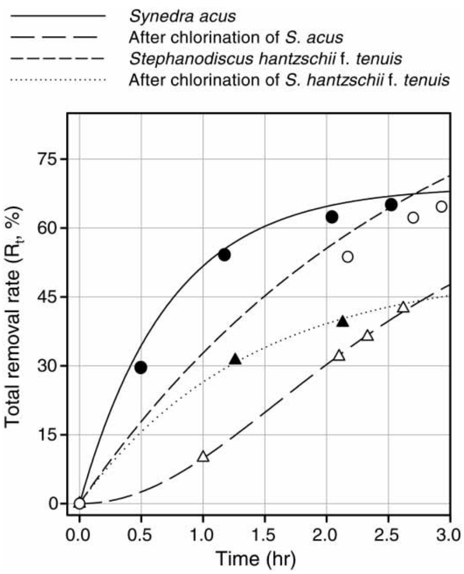

Figure 4 | Removal of algae by settling columns after chlorination and PAC coagulation in the jar test, using unialgal cultured species (fitted curves of the raw data).

in Korea. Instead, bad tastes and odors produced by algae have been managed using ozonation and GAC adsorption.

Despite the various methods for overcoming algal problems, dissolved organic matter such as algal metabolites and cellular exudates can cause other problems in the water treatment process. Thus, it is necessary to establish a clean water source rather than relying on procedures that eliminate algae and other fouling agents.

CONCLUSIONS

Research on problematic algae in water treatment processes was conducted at three localities: D plant (large facility), G plant (small facility) and a water organization with many plants in South Korea.

- Algae overflowing the SBs were exclusively diatom shells that are needle or long cylinder shaped, such as *Synedra acus, Nitzschia acicularis, Aulacoseira granulata* var. *angustissima* and others. Long cylindrical morphology, as an extreme deformation of the sphere, is related to physical buoyancy or delayed settling of diatoms and less dense floc formation in the process of coagulation and flocculation.

- The needle-shaped *Synedra acus* and discoid *Stephanodiscus hantzschii* f. *tenuis* are among the most troublesome algae in South Korea. Cell counts of about 200–500 cells/mL for *Synedra* and about 20,000 cells/mL for *Stephanodiscus* can cause serious problems in WTPs; these problems include clogging the sand filters. *Stephanodiscus* can penetrate deep into the filter beds of WTPs and prevent efficient water filtration.
- *Phormidium tenue*, a cyanobacterium, and its relatives, remained in the overflow water and cell counts in the SB occasionally exceeded those in the raw water. Most *Phormidium* filaments originated from periphytic algal assemblages that were attached to the basin wall.
- Siliceous diatom cells lose cellular materials with pre-chlorination treatment, giving them a lower density, so the settling removals of diatoms were significantly reduced after pre-chlorination, compared with intact algae.
- Conventional facilities did not completely resolve algal problems in water treatment processes, in which sedimentation is an intermediate sink and sand filtration is a final barrier for the removal of impurities and algae. Consequently, additional strategies are required to improve water treatment and to cope with the algal problem.

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