

Removal of organic matter from surface water during coagulation with sludge flotation and rapid filtration – a full-scale technological investigation

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ABSTRACT

Coagulation with sludge flotation and rapid filtration was selected as a surface water treatment technology to be optimised with a full-scale investigation, which was carried out in Poland between August and October 2013. The river water treated was characterized by low alkalinity, high-temperature variability and a high organic matter content. In the course of technological studies, the processes of coagulation with sludge flotation and rapid filtration were analysed. The studies were performed in the most adverse conditions for the applied technology i.e. during the period of algal bloom and subsequent decomposition of dead plankton. Throughout the study, the river water contained mainly dissolved organic matter, with occasional increases in the concentration of the undissolved fraction during algal bloom. The undissolved total organic carbon (TOC) fraction was effectively removed through coagulation while small doses of ClO_2 added prior to coagulation enhanced the process. The process of coagulation using high-coagulant doses at $\text{pH} = 6.5$ did not provide a reduction in the TOC value below the level of 4 mg C/L required for treated water. The effect was achieved by adding powdered activated carbon (PAC) before the filters. The coagulation products were characterised by low-hydraulic resistance which should be taken into account at the stage of water delivery to the filters, after flotation.

Key words | algal bloom, filtration, flotation, surface water treatment, total organic carbon

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INTRODUCTION

The basic processes used to effectively reduce the concentration of organic matter in water as part of surface water treatment technology include coagulation, adsorption and/or chemical oxidation and filtration (Sohn *et al.* 2007; Matilainen *et al.* 2010; Lawler *et al.* 2013; Wolska 2014). In recent years, attention has also been paid to the possibility of using the ion exchange process to remove natural organic matter (NOM) from water (Bolto *et al.* 2002; Croue *et al.* 1999; Comstock & Boyer 2014; Molczan & Szlachta 2011). Due to the presence of organic substances of different molecular weight and size, the effectiveness of their removal from water varies considerably (Hem & Efraimsson 2001; Huber *et al.* 2011; Vasyukova *et al.* 2013). Detailed descriptions of the issue can be found in numerous publications (Pruss *et al.* 2009; Guminska 2013; Klos & 2013; Teixeira & Miguel 2011; Baghoth *et al.* 2011; Abeynayaka *et al.* 2014). Their review leads to a conclusion that the proper way to

choose and optimise the appropriate surface water treatment technology is through technological studies.

The results of technological studies presented here illustrate the effectiveness of organic matter removal from surface water in the most challenging period for the water treatment technology selected in an earlier study (Pruss 2015), i.e. during the period of algal bloom and subsequent decomposition of dead plankton. Throughout the investigation, the water from the Polish river was characterized by low alkalinity and contained mainly dissolved organic matter, with occasional increases in the concentration of the undissolved fraction during algal bloom. Based on the studies conducted to date (Pruss & Pruss 2013; Pruss 2015), the following parameters of surface water treatment effectiveness were considered critical: total organic carbon (TOC), aluminium, total suspended solids (TSS) and sulphates (due to periodical use of high doses of aluminium sulphate).

The aim of the study was to optimise water treatment processes selected in this stage of the research and identify opportunities presented by rapid filtration and the use of powder activated carbon (PAC).

At present, the investment project involving the design and construction of water treatment facilities and technological equipment, based on the process of coagulation with sludge flotation and rapid filtration, is still in progress.

METHODS

The study was carried out at full scale (Figures A1–A3, available online at <http://www.iwaponline.com/wst/071/514.pdf>). Raw water from the river (at a maximum amount of 12 m³/h) was delivered to the contact tank where primary oxidation was carried out using chlorine dioxide added to the pipeline, prior to the static mixer. The dose of chlorine dioxide ranged from 0.9 to 2.0 mg/L. After primary oxidation, water was directed at a rate of 10 m³/h to the flotation tank where coagulation with sludge flotation was executed. Aluminium sulphate was used as a coagulant at doses between 4 and 11 mgAl/L. Subsequently, the water passed through a rapid filter with a hydro-anthracite N and quartz sand bed. Filtration velocity was 5.0 m/h. A filter made of methyl polyacrylate pipe with a diameter of 200 mm and a height of 3 m was filled with 200 mm of gravel, 300 mm of hydro-anthracite N (effective size $d_e = 1.9$ mm, uniformity coefficient < 1.5) and 700 mm of quartz sand (effective size $d_e = 0.955$ mm, uniformity coefficient = 1.28). The column was provided with piezometers. After 72 hours of operation or when resistance rose to 1.5 m H₂O, the filter was backwashed with air and water with an intensity ensuring filter bed expansion by 35–50%. Incidentally, the filters were previously dosed with powdered activated carbon (PAC) Norit W 15 (iodine number 1200, molasses number 200, methylene blue adsorption 22 g/100 g; total surface area BET 1150 m²/g, particle size $D_{50} = 15$ μm). Hydraulic retention time for PAC before it entered the sand bed was about 10 minutes.

Samples for analysis were collected from raw water, from water after coagulation in the flotation tank and at the rapid filter outlet. Samples were generally collected once a day and (for TSS determination) twice a day. The physico-chemical analyses and hydrobiological analyses were carried out by accredited Polish laboratories. The analytical methodology conformed with the standard method.

The flow chart of the entire experimental set-up showing the sampling points where water samples for analysis were collected is presented in Figure 1.

Water treatment effectiveness studies were carried out in six alternative options differing in respect of the coagulant dose (4–11 mg Al/L) and pH value during the coagulation process. Detailed information of the analyzed options are shown in the Supplementary Material (Tables A1–A3, available online at <http://www.iwaponline.com/wst/071/514.pdf>).

RESULTS AND DISCUSSION

Determined TOC and dissolved organic carbon (DOC) values are shown in Figure 2 against the background of the concurrent changes in the pH of water and the algal bloom and plankton decay periods (Figures A4 and A5, available online at <http://www.iwaponline.com/wst/071/514.pdf>).

Changes in the biomass concentration was observed over the period of the algal bloom and its subsequent decay, with a focus on the predominant cyanobacteria. In cycle 4 of the microbial biomass it was 16.2 mm³/L (biomass of cyanobacteria was 14.58 mm³/L), whilst in cycle 18 the microbial biomass was 18.1 mm³/L (biomass of cyanobacteria was 17.28 mm³/L). The biomasses of 2.17 mm³/L measured on cycle 22 and 1.13 mm³/L measured on cycle 27 confirmed the plankton decay. The pH value of 7.5 indicates the end of the bloom period.

The analysis of the results shown in Figure 2 indicates that the occurrence of the bloom contributed to an increase in TOC to an average value of 16.7 mg C/L, with two peak values of 26.8 and 29.2 mg C/L. After the end of the bloom decay period, the TOC reached 9.8 mg C/L on average, i.e. went down by 41%. Changes in the DOC values were less pronounced. The average concentration during the bloom was 12.2 mg C/L and after the bloom 9.4 mg C/L, i.e. a 23% reduction was observed. Worth noting is the increase of DOC fraction in the TOC. During the bloom, DOC accounted for 73% of TOC on average, whilst after the bloom the value rose to 96%.

The water treatment effectiveness studies were carried out in six alternative options. The results are summarised in Figures 3 and 4.

Initially, two coagulation cycles were carried out with doses of 5 mg Al/L and 6.5 mg Al/L, respectively, which, according to a vessel test, ensured proper flocculation at pH = 7.3–7.6. The result was a decrease in TOC by 20–55%.

Option 1

In view of the above and taking into account the occurrence of the algal bloom, the coagulant doses in Option 1 were

**A FLOW CHART OF A PILOT SETUP FOR PRE-TREATMENT OF RIVER WATER
COAGULATION + FLOTATION + FILTRATION
STAGE 3 OF FULL SCALE TECHNOLOGICAL INVESTIGATION**

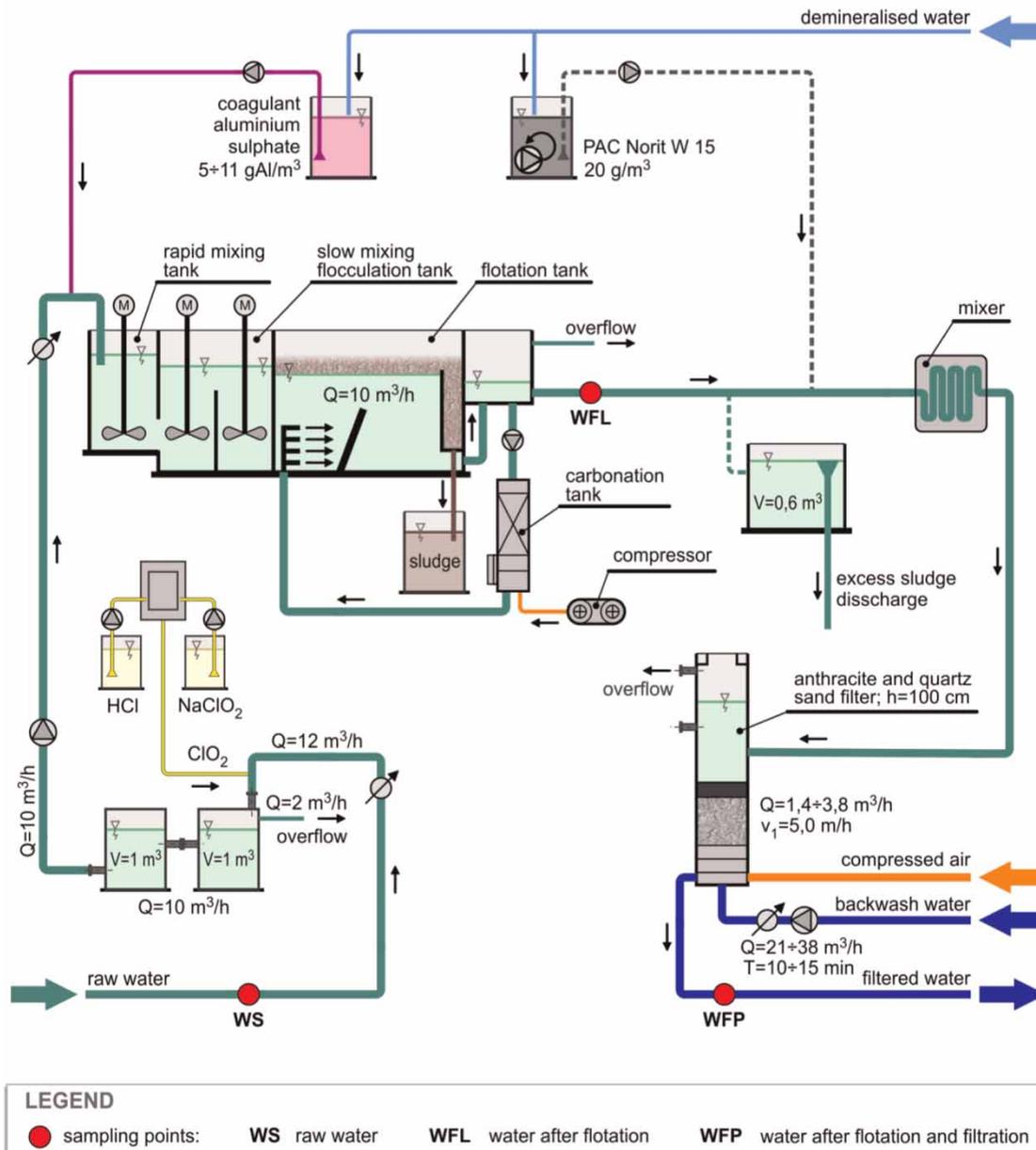


Figure 1 | A system of surface water pretreatment – a full-scale technological investigation.

increased to 11 mg Al/L. Upon identifying a need to adjust the pH value using a NaHCO_3 solution to 6.5, the doses of the coagulant were gradually reduced from 10.5 to 9.7 mg Al/L. The resulting pH values ranged from 6.1 to 6.4. Consequently, the effectiveness of TOC and DOC removal increased significantly. With the exception of the peak value recorded on 27 August

(cycle 3), the TOC concentrations were reduced by 65–75% and the DOC by 60–65%. In addition, as shown in Figure 4, the concentrations of TSS and aluminium were reduced to average values of less than 3 mg/L and approximately 0.3 mg Al/L, respectively. After filtration, the residual aluminium content did not exceed 0.07 mg Al/L.

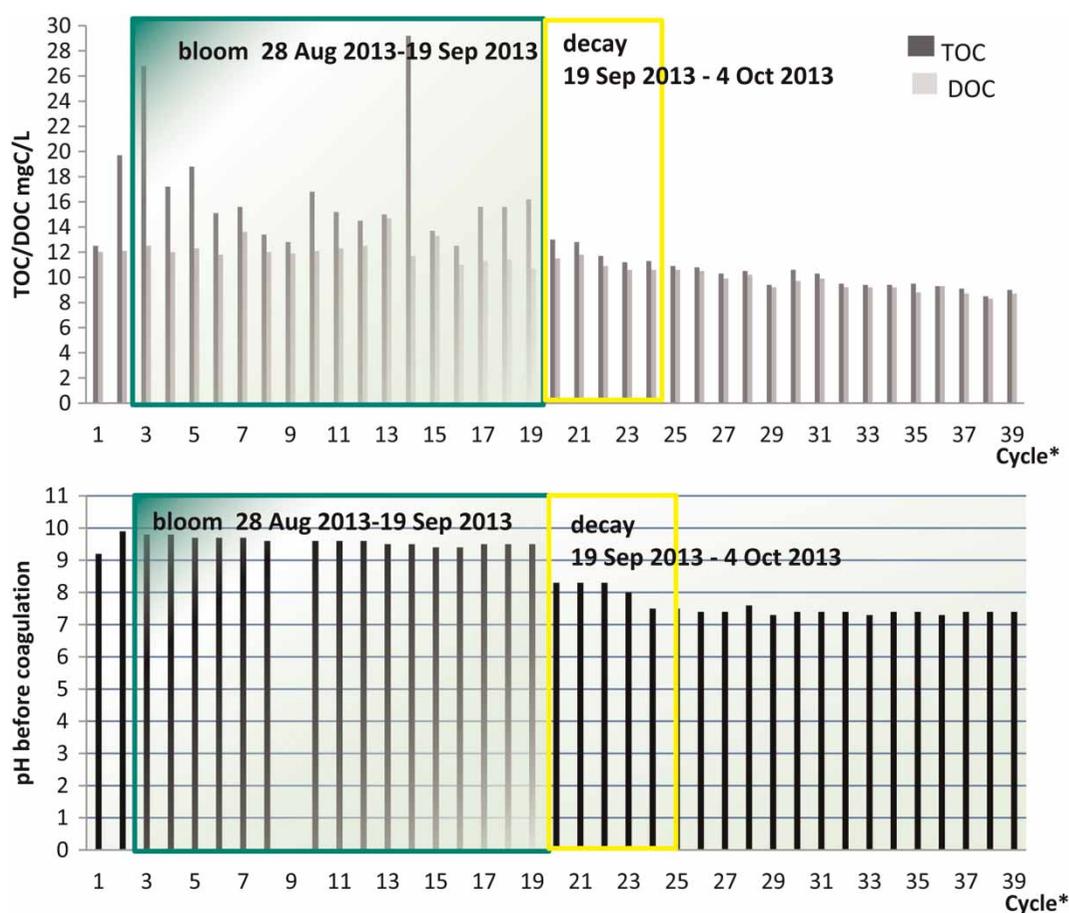


Figure 2 | TOC and DOC concentrations and pH in water from the river. *On the horizontal axes, numbers of cycles are indicated instead of dates.

Option 2

In the second option, the coagulant doses were reduced to 4–6 mg Al/L. The effectiveness of TOC and DOC removal dropped significantly, as represented by the maximum concentration values in cycles 12 and 13 in Figure 3.

TOC values went down by approximately 43% and DOC from 35 to 42%. The process of sludge flotation was unstable. The concentration of suspended solids past the flotation tank periodically amounted to 10 mg/L and that of aluminium exceeded 1 mg Al/L (Figure 4). After pH adjustment using HCl to 6.6–6.7 in cycles 15 and 16, the effectiveness of coagulation approximated that of cycles 12 and 13, the concentration of suspended solids past the flotation tank ranged from 4 to 6 mg/L and of aluminium around 0.7 mg Al/L (Figure 4).

The suspended solids separated in the flotation tank demonstrated low-hydraulic resistance and, as a result, during the delivery of water to the filter, were subject to dispersion. Consequently, they passed through the filter bed

and the concentrations of residual aluminium in the filtrate varied from 0.12 to 0.44 mg Al/L (Figure 4).

An increase in the coagulant dose to 6 mg Al/L and pH adjustment to 6.4 allowed for a reduction in TOC concentration by 60% and, in cycle 19, even by 68%. DOC concentrations versus raw water were lower by 46–47% (Figure 3). The effectiveness of flotation also improved, as evident in the TSS concentration past the flotation tank which remained below 2 mg/L and that of aluminium below 0.2 mg Al/L. Probably, the flock structure also changed since after filtration the residual aluminium concentrations ranged from 0.04 to 0.06 mg Al/L (Figure 4). Cycle 14 was not evaluated due to the incidental growth in the TOC value for the raw water to 29.2 mg C/L, with a concurrent relatively low DOC concentration of 11.7 mg C/L.

Option 3

The third option involved a study carried out after the end of the bloom period, during the plankton decay. The

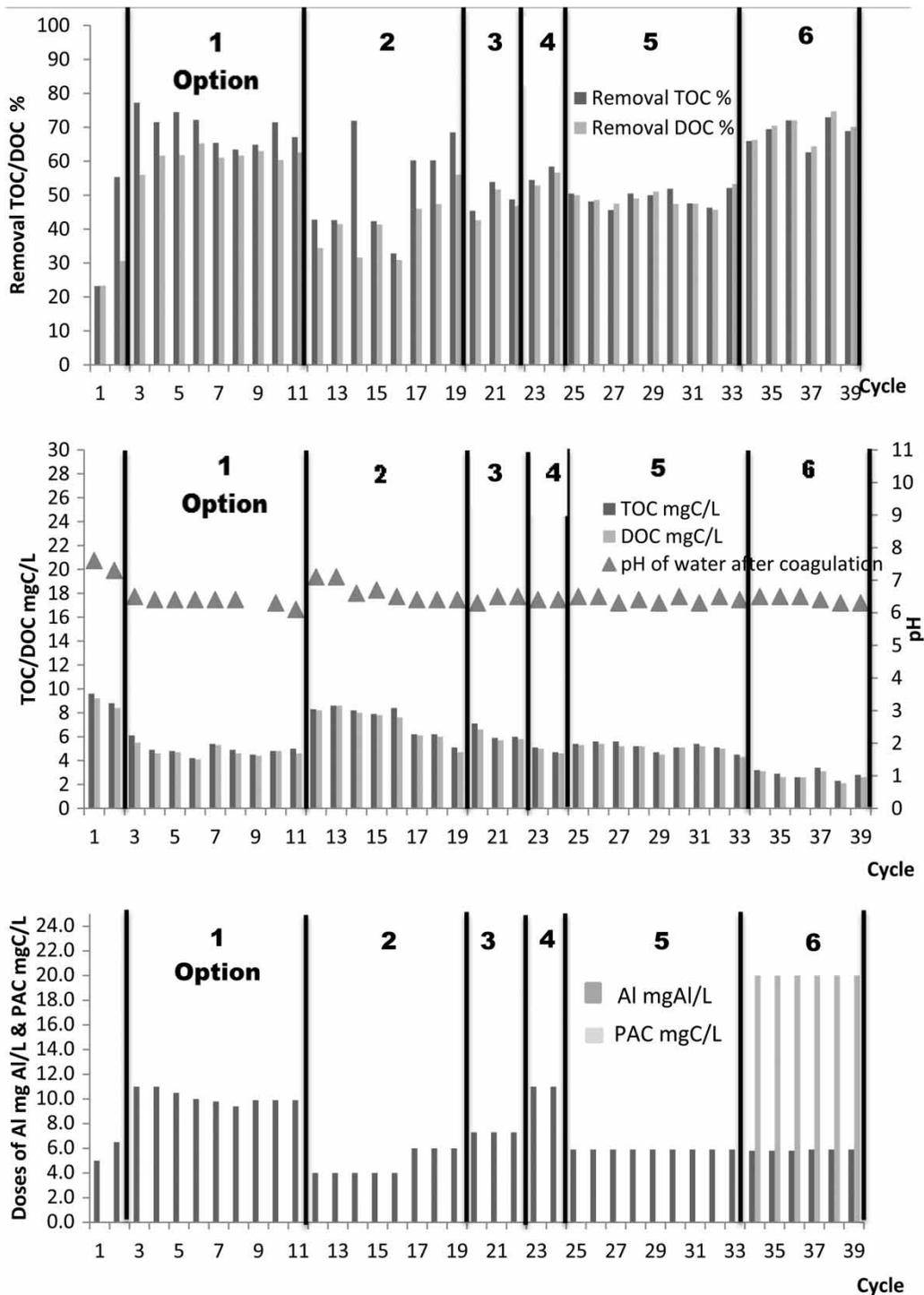


Figure 3 | Removal of TOC, DOC after coagulation and filtration, doses of the coagulant (aluminium sulphate) and PAC and pH value of the water after coagulation.

content of organic matter in raw water decreased considerably, just like the share of insoluble substances making up the TOC. Alkalinity also went down. The applied coagulant dose of 7.3 mg Al/L in cycles 20–22

ensured pH reduction to 6.3–6.5. The TOC value decreased by 45–54% and the DOC by 43–52%. The result of the coagulation process differed from that observed in cycle 19, undoubtedly as a result of a lower

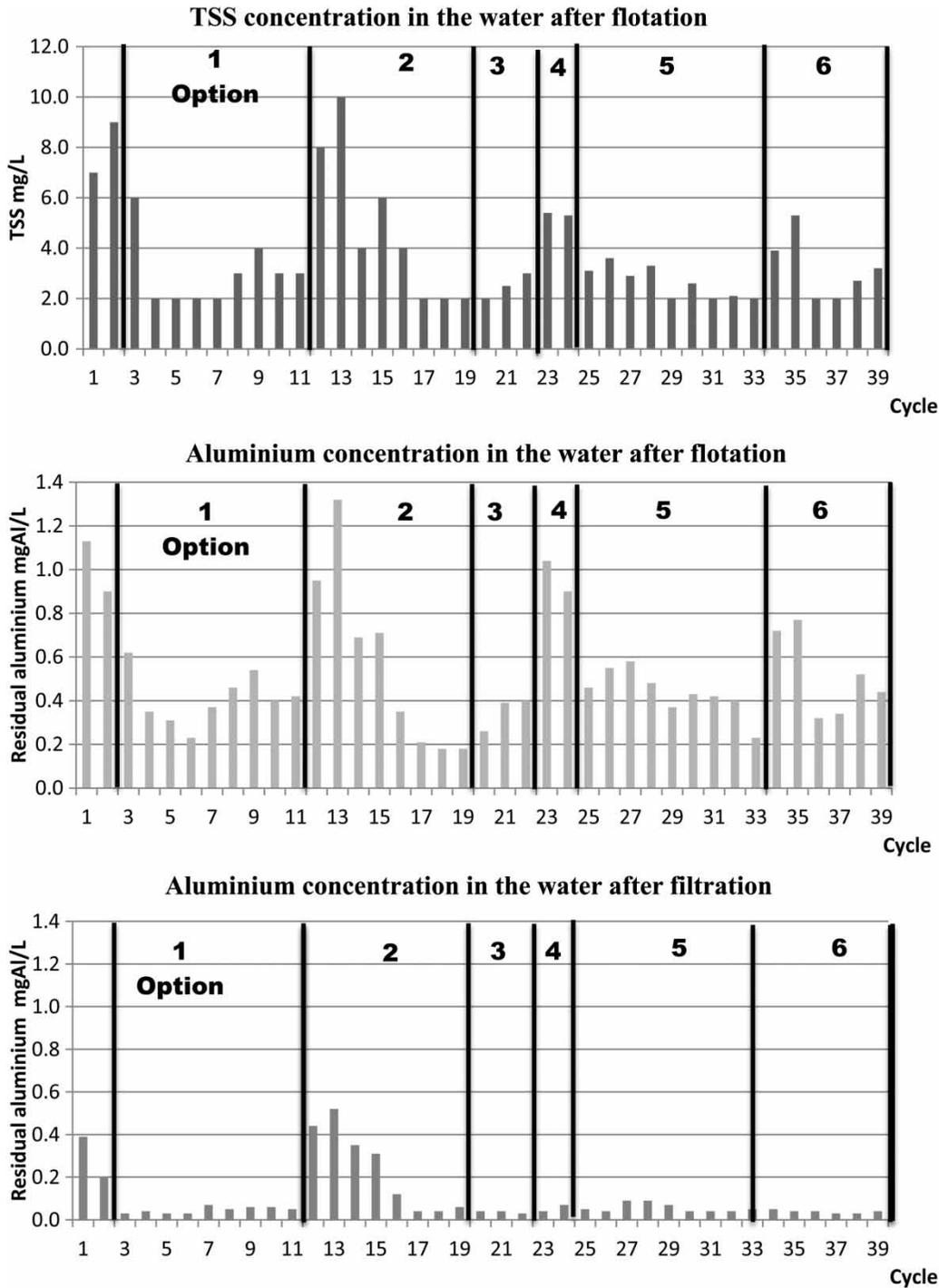


Figure 4 | TSS, and residual aluminium in the water after flotation and after filtration.

content of insoluble substances in TOC, since the effectiveness of DOC removal in both cases was similar. After filtration, the TSS concentration ranged from 3 to less than 2 mg/L and that of aluminium after filtration between 0.03 and 0.04 mg Al/L.

Option 4

In option 4, in cycles 23 and 24, the dose of the coagulant was increased to 11 mg Al/L in order to enhance the effectiveness of TOC removal from water. Adjustment of the pH

value to 6.4 using the NaHCO_3 solution turned out to be necessary.

In cycles 23 and 24, to provide adequate water alkalinity and to complete hydrolysis of the coagulant in water, NaHCO_3 was added. This ensured suitable pH of about 6.4. At that time, the alkalinity of the raw water was 1.45 mval/L, pH 7.5–8.0.

The results presented in Figures 3 and 4 indicate, a noticeable increase in the coagulation effectiveness. The TOC values were lower than those recorded in cycles 20–22. Compared to raw water, TOC concentrations went down by 56–58% and DOC by 53–57%. The concentrations of suspended solids after flotation, however, were higher than those measured in the previous cycles and ranged from 5.3 to 5.4 mg/L, while the aluminium content varied from 0.9 to 1.04 mg Al/L. Given that, after filtration, the concentrations of residual aluminium decreased significantly to 0.04–0.07 mg Al/L, the results for suspended solids are unsatisfactory, demonstrating that there are faults/disruptions in the flotation process.

Option 5

Option 5 was carried out after the end of the algal bloom period, when the concentration of organic matter in the water gradually decreased. The results are presented in Figures 3 and 4. The coagulant dose reduced to 5.9 mg Al/L ensuring a pH at the level of ≈ 6.5 . After coagulation and filtration, the TOC values ranged from 5.6 to 4.5 mg C/L and DOC from 5.4 to 4.3 mg C/L. The TOC removal effectiveness varied from 48 to 52% and the corresponding rates for DOC ranged from 48 to 53%. The similar removal effectiveness rates for both carbon forms resulted from the fact that DOC accounted for 96–100% of the TOC.

Flotation turned out to be an effective process because the concentration of suspended solids past the flotation tank exceeded 3 mg/L only in three cases, while in all other cases it was significantly lower.

Aluminium concentrations ranged from 0.58 to 0.23 mg Al/L. No clear correlation, however, was observed between the aluminium concentration and the TSS value since, for instance, when TSS amounted to ≤ 2 mg/L, the corresponding aluminium contents were 0.42, 0.40, 0.37 and 0.23 mg Al/L.

After filtration, the concentration of residual aluminium varied from 0.09 to 0.04 mg Al/L. As mentioned in Option 2, the variances probably resulted from dispersion of suspended solids during the water transport between the flotation tank and the filter.

Option 6

The Option 6 study involved cycles 34–39 and was carried out in the period of stabilization of organic matter content in raw water. Using the same coagulant doses as in Option 5, after flotation the TOC values decreased by 45–52%; however, they were still higher than the limit acceptable for treated water. The results are presented in Figure 3.

After adding PAC dosed into the water before the filter, the effectiveness of organic carbon removal from water grew by 69–73%, resulting in TOC concentrations of 2.3–3.4 mg C/L and DOC of 2.0–3.1 mg C/L. A comparison of TOC and DOC values in the analysis of an approximately 60-hour filter cycle in cycles 34, 35 and 36 demonstrates a progressive increase in the effectiveness of pollutant removal. It can thus be concluded that carbon deposited in the filter bed was still active and contributed to the adsorption of organic carbon during filtration of the water.

The quality of the filtered water shows the detention of PAC in the filter (low turbidity of the filtrate, the low concentration of TOC). This was owing to the fact that the water flowing into the filter was characterized by a concentration of suspensions of products of coagulation of from 2.0 to 5.3 mg/L, which may possibly 'sealing' the bed, and giving a longer retention time for the PAC in the filter.

In cycle 39, the effectiveness of concurrent dosage of ClO_2 into raw water and activated carbon before the filter was evaluated. The TOC and DOC concentrations in water after filtration did not differ from the concentrations in cycles 35, 36 and 37. It can thus be concluded that 2.0 mg of ClO_2/L added to the water before the contact tank and flotation tank with a total holding time of approximately 40 minutes (with a resulting redox potential of water before the filter amounting to 687 mV) did not reduce the sorption capacity of carbon in a noticeable way. It should, however, be borne in mind that ClO_2 dosage began after 24 hours of adding carbon to the water, which deposited in the bed and, as mentioned above, being still active could have compensated for the potential adverse impact of ClO_2 .

CONCLUSIONS

The analysed raw water was characterised by a high content of dissolved organic matter, with incidental peaks of the undissolved fraction during the algal bloom.

The processes of coagulation with sludge flotation and rapid filtration were analysed. Water treatment effectiveness

studies were carried out in six alternative options differing in respect of the coagulant dose (4–11 mg Al/L) and pH value during the coagulation process. The undissolved TOC fraction was effectively (58%) removed in the course of the coagulation with flocculation process and small ClO₂ doses prior to coagulation enhanced the process.

Coagulation with flocculation using high coagulant doses (up to 11 mg Al/L) at pH = 6.5 did not result in a reduction of the TOC below 4 mg C/L which is a limit required for treated water. Such an effect was obtained by adding PAC before the filter.

It has been found that in order to maintain the required parameters of the treated water (TOC ≤ 4.0 mgC/L; TSS ≤ 2.0 mg/L; Total aluminium ≤ 0.1 mgAl/L), it is necessary to use PAC and rapid filtration after coagulation and flotation.

The coagulation products were characterised by low-hydraulic resistance which should be taken into account while transporting the water after flotation to the filters.

ACKNOWLEDGEMENTS

The author wishes to thank Professor Marian Błażejowski and the AQUA S.A. companies from Poznan for the friendly atmosphere and their effective collaboration during this full-scale technological investigation.

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First received 28 August 2014; accepted in revised form 4 December 2014. Available online 23 December 2014