Application of recycled sludge to stabilize coagulation process

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ABSTRACT

In conventional treatment of variable quality mountain water, an inability to immediately adjust the coagulant dose to variations in water quality causes overdose or underdose of coagulant in relation to its optimal value. The results of the research showed that the reuse of post-coagulation sludge was an effective method to maintain high and stable coagulation effectiveness under both polyaluminium chloride (PACl) overdose and underdose conditions. Recycled sludge contains a large portion of insoluble aluminium hydroxides that could be utilized in underdose PACl conditions. Post-coagulation sludge recycled to a flocculation tank enabled the reduction of a dose of low basicity PACl by 15% compared to a dose required in conventional coagulation. In periods of coagulant overdosing, sludge addition prevented an increase in the number of fine particles in an outflow from sedimentation tanks that could not be retained in a filter bed.

Key words | coagulant dose control, particle counter, pre-hydrolyzed coagulant, recycled sludge

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INTRODUCTION

During coagulation of low temperature water, the effectiveness of the removal of mineral particles and organic matter can become weaker due to a slow hydrolysing process, high aggregation shear and slow settling velocity (Maćkiewicz & Dziubek 2004; Dziubek & Maćkiewicz 2007). Because of the poor buffer action of raw water, there is a tendency to minimize coagulant doses and to carry out a coagulation process in filter beds (direct filtration). Based on existing conventional treatment processes in drinking water treatment plants, the reuse of post-coagulation sludge is an alternative method to enhance coagulation efficiency during cold periods. Recycled sludge contains a large portion of insoluble aluminium hydroxides that can be utilized to enhance pollutant removal. This process enables operational costs to be lowered due to lower coagulant addition and sludge disposal (Chu 2001; Guan *et al.* 2005; Zhou *et al.* 2012).

The properties of post-coagulation sludge depend on the quality of raw water and applied reagents. The possibility of using sludge formed in conventional coagulation, i.e. flocculation and sedimentation, is due to the fact that sludge particles still reveal adhesion and adsorption abilities. They can not only adsorb colloids or suspensions contained in purified water, but primarily affect rapid formation and agglomeration of resulting flocs. The precipitates added to a flocculation chamber may successfully replace the addition of flocculants. Particles of post-coagulation sludge act as flocculation nuclei, and accelerate chemical reactions and formation of larger aggregates. Flocculation occurs the sooner the flocs are larger and heavier, and thus flocculation and sedimentation periods may be shortened. However, sludge structure is not stable and undergoes an aging process (syneresis). The results of previous studies showed that with ageing, the neutralizing and sorption abilities of reused sludge decreased, so the effect of coagulation with recycled sludge deteriorated (Sozański 1999; Gumińska & Kłos 2008; Gumińska 2009).

Based on the analysis of electrokinetic potential it was stated that sludge particles produced during coagulation and flocculation also reveal unexploded neutralization properties which depend on coagulant characteristics. Sludge

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particles produced by high-polymerized polyaluminium chlorides (PACl) show a much greater capacity to neutralize the charge of impurities present in raw water than precipitates formed after the process of coagulation with aluminium sulphate (Gumińska & Gumiński 2015). It is important in colloid removal when charge neutralization is a dominant mechanism of coagulation. Lower doses of pre-polymerized coagulants in comparison to hydrolysed coagulants may then be applied. In the case of low basicity coagulants the role of recycled sludge is different. Its role is not only to enhance flocculation but also to increase the sorption capacity of aggregates and hence removal of dissolved organic natural matter substances via the mechanism of sweep coagulation.

At water treatment plants a standard method to determine a coagulant dose is jar testing. Such a method is reliable for waters of quite stable quality. The problems arising from treatment with an inadequate dose of coagulant frequently concern treatment stations supplied with mountain water. Such waters reveal low buffer capacity, low temperature and high variability of composition in short periods of time. An inability to immediately adjust a coagulant dose to variations in water quality causes adverse effects of overdose and underdose of PACl in relation to its optimal value.

The paper presents the results of the study on the use of recycled sludge to stabilize the coagulation process by low basicity PACl during treatment of mountain water. The impact of recycled sludge on treatment effectiveness in underdose and overdose conditions was analysed.

MATERIALS AND METHODS

Water characteristics

Raw water was typical mountain water. Over a year raw water characteristics vary in colour and content of organic matter. Episodes of increased turbidity during periods of heavy rainfall and melting of snow are also noted. SUVA (Specific UV Absorbance) values are higher than 3.0 dm^3/mg C·m, which indicates that the water is rich in DBP (disinfection by-product) precursors. That is why the primary purpose of coagulation is to remove humic acids – the main organics responsible for production of disinfection by-products.

The study was conducted during winter time to avoid sudden water quality changes.

As shown by the data in Table 1, in the study, water samples displayed very low alkalinity (very low buffer capacity) and turbidity, high colour, variable absorbance UV_{254} and low temperature. With its poor buffer action, the water was strongly corrosive.

Reagents and analysis

The process of coagulation was carried out by low basicity PACl. Its characteristics are shown in Table 2.

Laboratory study

The purpose of the laboratory study was to estimate to what extent it is possible to lower PACl dose if recycled sludge was applied. A coagulant dose was optimized for minimum settled water turbidity and absorbance UV_{254}. The operational procedures of jar tests were as follows: 0.7 L of raw water was transferred into a 1.2 L square beaker with a sampling port 3 cm below the water surface; the jar tester was started at a rapid mixing of 270 rpm; after 30 s coagulant was added followed by a mixing speed of 200 rpm for 2 min and then 30 rpm for 20 min; and after 30 min of quiescent settling, samples were taken for water quality measurement. After settling, the residual absorbance UV_{254} and turbidity of the supernatant were measured.

At the second stage of a laboratory study, an optimal PACl dose was added to six beakers to produce a suitable

Table 1 | Characteristics of raw water

Parameter	Temperature, °C	pH	Total hardness, $mgCaCO_3$/L	Alkalinity, mval/L	Turbidity, UV_{254} m^{-1}	Absorbance, UV_{254} m^{-1}	Colour, mg Pt/L
	3.1–3.3	6.9–7.1	50–60	0.5–0.6	5.4–8.1	4.0–11.8	42–50

Table 2 | PACl characteristics

Gravity, g/ml	1.24
pH	2.6
Al, % wt.	5.5
Cl, % wt.	13.1
Al/Cl	0.42
Basicity, %	71.0

volume of sludge to be utilized in further assays. After sedimentation 0.6 L of supernatant water was decanted. Precipitated sludge was transferred to a separate beaker while stirring at 60 rpm.

At the third stage, at rapid stirring, PACl was applied to six beakers in doses corresponding to 40%, 50%, 60%, 70%, 80% and 100% of an optimal dose, respectively. Then the rotational speed was reduced to 60 rpm (to avoid floc breakage) and 50 ml of the previously collected post-coagulation sludge was injected into each beaker. After sludge dosing, flocculation started at 30 rpm. After settling, residual absorbance UV_{254} and turbidity of the supernatant were analysed. For comparative purposes, coagulation by PACl doses at 40%, 50%, 60%, 70%, 80% and 100% of an optimal dose (without recycled sludge) was carried out. The laboratory tests were repeated in six series and mean values of water quality parameters (absorbance UV_{254}, turbidity) were calculated.

Pilot study

The aim of the pilot study was to analyse the possibility of using the properties of recycled sludge to stabilize coagulation effectiveness. The treatment process was carried out in a conventional coagulation system. It consisted of a rapid- and a slow-mixing chamber and a lamella sedimentation chamber. A system of post-coagulation sludge recirculation was also applied (Figure 1). The system operated continuously at a flow of 750 L/h. The flocculation time was approximately 20 minutes and the hydraulic load of the settler was 1.5 m^3/m^2h. Precipitated sludge from a hopper was partly recycled to a flocculation chamber. The degree of recirculation was defined as the ratio of the flow of post-coagulation sludge to the flow of purified water. On the basis of a preliminary study it was stated that a 6% recirculation degree was optimal. Taking into account other tested values (5.3% and 8%) a deterioration of treatment effectiveness was observed. To determine the effect of recycled sludge on coagulation effectiveness, at the first stage, the treatment process was carried out without sludge recirculation. Excess sludge was removed periodically. The measuring and control system consisted of a streaming current analyser (SCA) and particle counters and on-line UV_{254} analysers.

SCA is designed for continuous analysis of the electrokinetic charge of particles suspended in water, which is what makes it possible to monitor, measure and/or control a coagulation process. This is the only device that directly

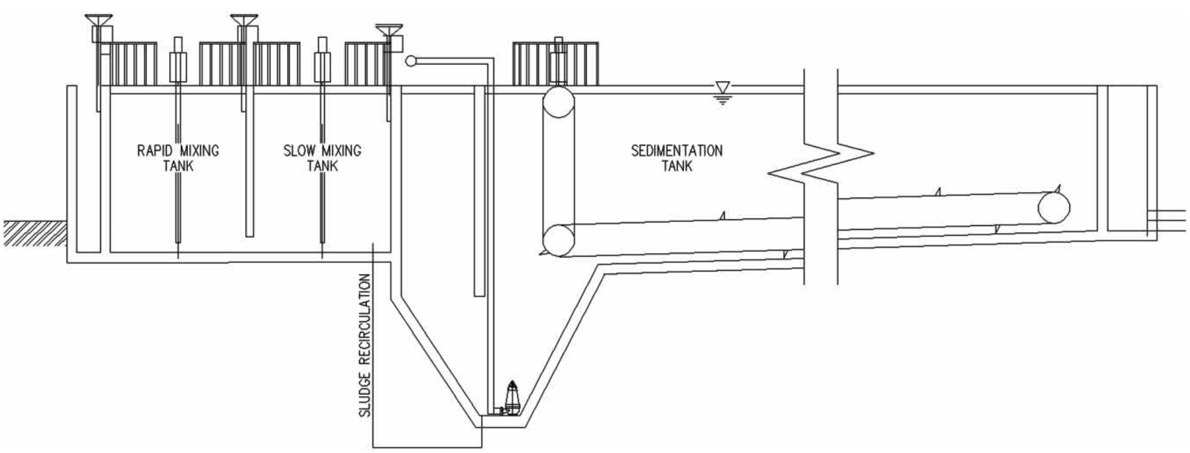

Figure 1 | Schematic diagram of a treatment system.

measures the effect of coagulant addition on the surface charge of colloidal particles in raw water.

Samples were collected and analysed four to five times daily. To evaluate the effectiveness of treatment, measurements of turbidity, absorbance UV_{254} and colour were made.

A number of 10 μm particles were measured to monitor the flocculation process. In addition, a number of 1 μm particles were analysed to control the PACl dose. As shown in previous research, these particles are precipitated hydrolysis products of pre-hydrolysed coagulants. If too low a coagulant dose is applied, an increase in 1 μm particle number in clarified water is the result of too low a concentration of precipitates, not susceptible to agglomeration and precipitation. It is accompanied by inefficient turbidity, absorbance and colour removal. In PACl overdosing, an increase in 1 μm particle number is often the only indicator of an improper course of coagulation. These particles appear in the outflow from sedimentation tanks and cannot be retained in the filter bed due to their high surface charge. Consequently, the filtration process has to be stopped despite the inexhaustible bed capacity. Due to their size, non-agglomerated particles are not usually identified by turbidity measurement (Gumińska & Kłos 2015). At present, a routine action to reduce the impact of this phenomenon is the dosage of anionic polyelectrolytes. Their task is the agglomeration of fine particles by bridging and sweep coagulation. This method is quite effective, if it is possible to control and adjust a dose of flocculant not only to a variable water quality, but also to a variable dose of coagulant. Otherwise, unagglomerated polymer particles may pass through rapid filters, which may not always stop the hydrolysis products of the flocculant.

It is worth emphasizing that a particle counter has been proved by many researchers also to be a very good tool to control *Cryptosporidium* risk. Increased concern about the possible passage of disinfectant-resistant pathogens, such as *Cryptosporidium*, through filters has focused attention on many aspects of operational practices, including the recycling of waste or spent filter backwash water within drinking water treatment plants (Cornwell & Lee 1994; Cornwell & MacPhee 2002; Hamilton *et al.* 2002).

In the study turbidity was measured using a turbidimeter 2100AN (HACH) and absorbance via a spectrophotometer DR5000 (HACH). Particle numbers of 1 μm and 10 μm were analysed on-line by a particle counter ARTI WPC21 (HACH).

RESULTS AND DISCUSSION

Laboratory study

The results presented in Figures 2 and 3 show that coagulation at an optimal PACl dose was very effective in absorbance UV_{254} removal. It was reduced by 76.5%. Turbidity removal was only 36%. Such a poor effect of

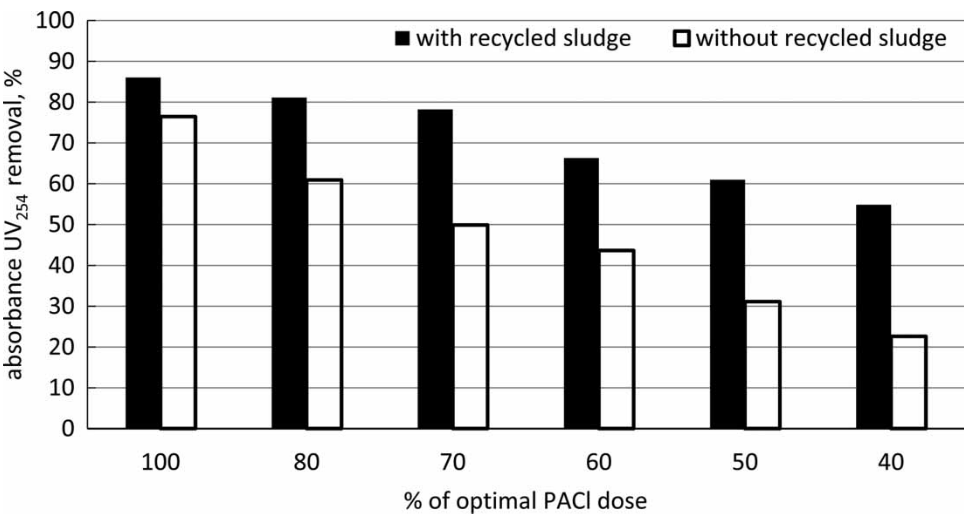

Figure 2 | Effect of recycled sludge dosage on absorbance UV_{254} removal – laboratory study.

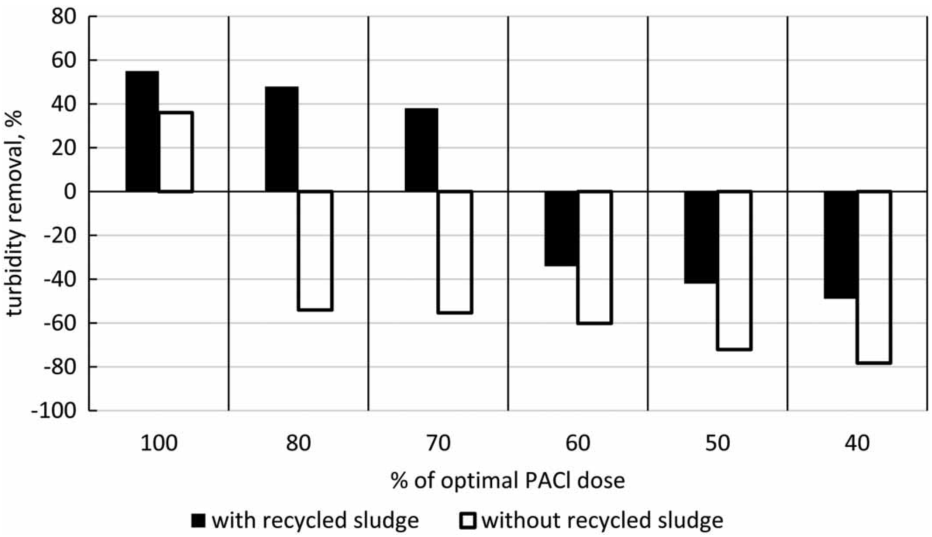

Figure 3 | Effect of recycled sludge dosage on turbidity removal – laboratory study.

turbidity reduction resulted from raw water characteristics. A low concentration of mineral particles that could act as nuclei in the coagulation process worsened flocculation and hence the sedimentation process. In such difficult conditions, recycled sludge enhanced flocculation and enabled greater effectiveness of contaminant removal. As compared to conventional treatment recycled sludge improved absorbance and turbidity removal. Coagulation at 80% of the optimal coagulant dose (without sludge addition) caused considerable deterioration of treatment effectiveness. Turbidity was even higher than in raw water and increased by 54%. In relation to the effects obtained at the optimal PACl dose, absorbance removal deteriorated by 15.6%. Post-coagulation sludge dosing significantly improved mineral particle and dissolved organic substance removal efficacy. Absorbance and turbidity values were even lower than the values obtained at the optimal coagulant dose. When recycled sludge and 70% of the optimal PACl dose were added, absorbance and turbidity removal was comparable to the efficacy obtained during coagulation at the optimal coagulant dose (without sludge dosing). Further lowering of a coagulant dose without and with sludge addition worsened the effectiveness of the purification process. As compared to conventional coagulation, sludge dosing always positively influenced absorbance removal. However, at such low PACl doses a significant increase of turbidity was observed, which exceeded values noted in raw water.

Taking into consideration the results of laboratory studies it was concluded that coagulation with recycled sludge was very effective even if the coagulant dose was lower than 30% in relation to its optimal value stated in conventional coagulation.

Pilot study

Conventional coagulation

A PACl dose was stated on the basis of jar testing at the beginning of a pilot study (without recycled sludge). To analyse the influence of recycled sludge on coagulation effectiveness, the optimal dose determined in jar tests was lowered by 20%. It was decided that the coagulant dose should not be lowered by 30% as it resulted from the laboratory study. The results of the laboratory study could not be directly transferred to pilot-scale research because on a laboratory scale, post-coagulation sludge was used only once. In a pilot-scale system, a portion of precipitated sludge was repeatedly recycled from a sediment hopper to a mixing chamber. Consequently, the surface charge of post-coagulation sludge particles decreased as a result of their previous usage to neutralize the charge of water impurities. Sorption capacity was also lowered. The ability of sludge to remove impurities worsened over time. On the other hand, fresh precipitates were deposited in the hopper, so recycled sludge was a mixture of fresh and partially exploded sludge.

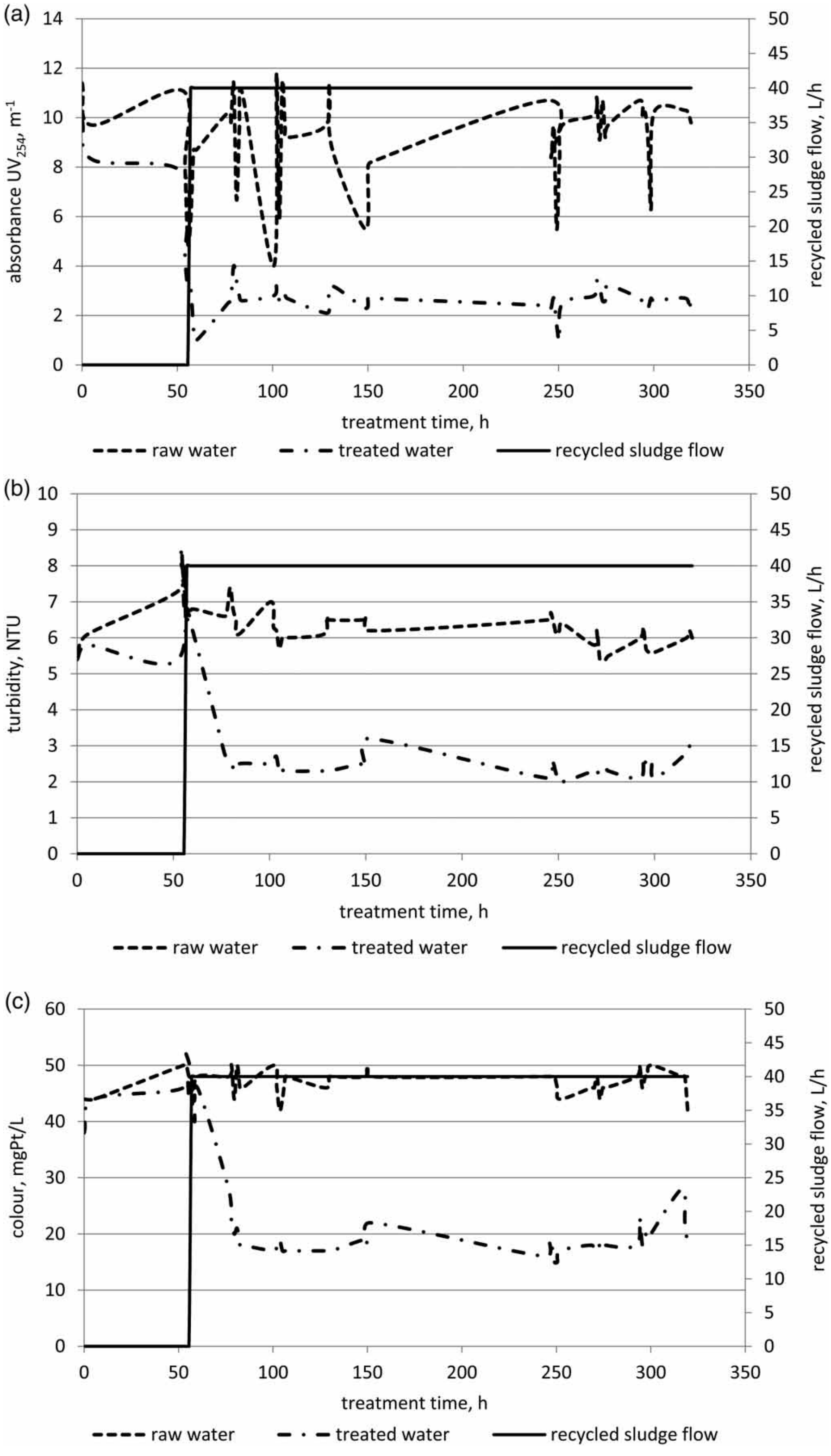

Figure 4 | (a) Effect of recycled sludge dosage on absorbance UV_{254} removal; (b) effect of recycled sludge dosage on turbidity removal; (c) effect of recycled sludge dosage on colour removal; (d) effect of recycled sludge dosage on 1 μm particle removal; (e) effect of recycled sludge dosage on 10 μm particle removal. *(Continued.)*

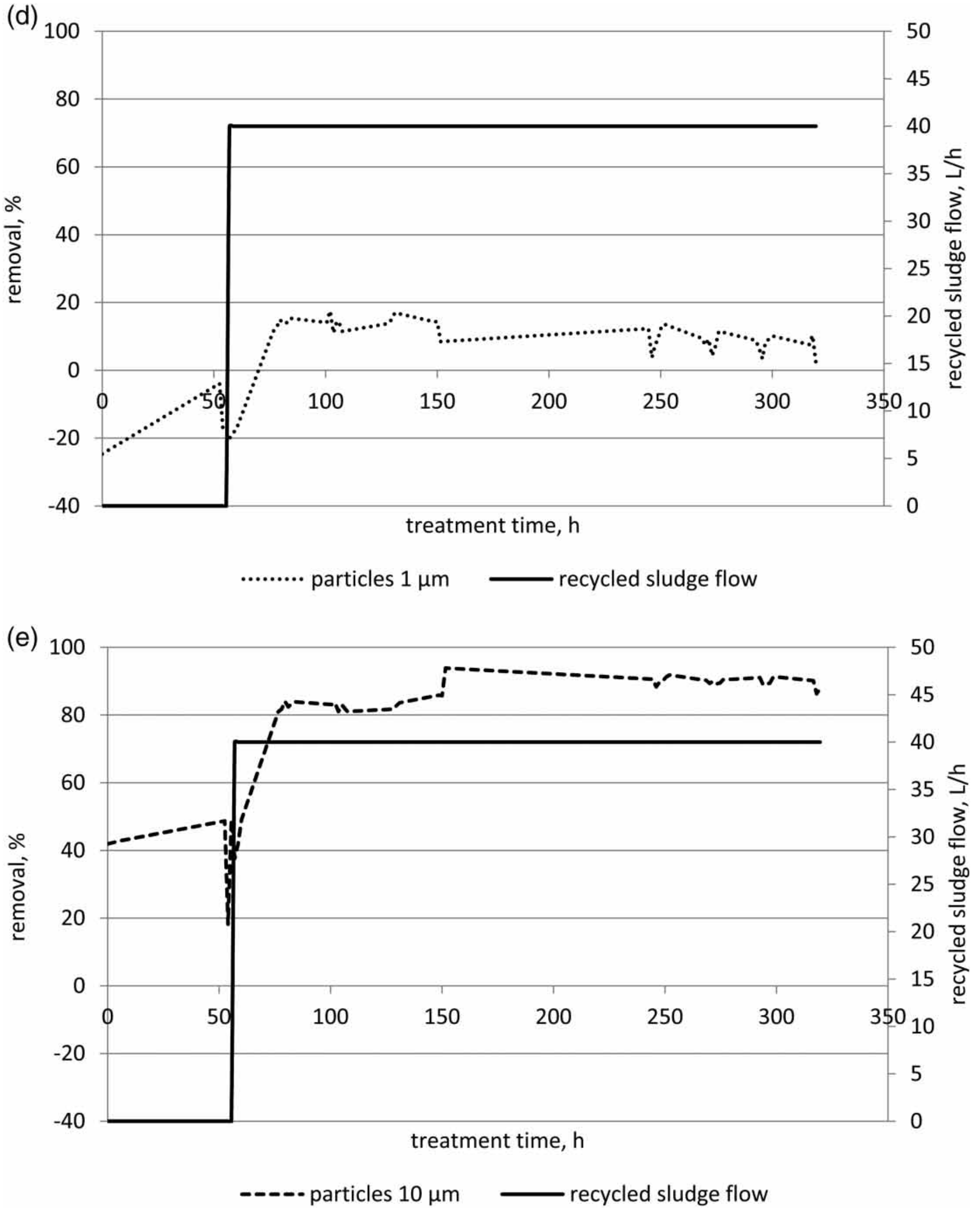

Figure 4 | Continued.

A fixed PACl dose (18 mg/L) was maintained for the whole research period. Additionally, jar tests were made every day in order to note the impact of water quality changes on the coagulant dose. Although raw water turbidity variability was negligible, absorbance changes turned out to have a visible impact on the PACl dose.

The first stage of a pilot study was conducted in a conventional coagulation system (without recycled sludge) for 56 hours. As a result of coagulant underdosing, the treatment was ineffective (Figure 4(a)–4(e)). Absorbance UV_{254} removal was also ineffective and decreased from 4.9–11.4 m^{-1} to 3.1–9.9 m^{-1}. Also no significant effects of colour removal were observed. Its values were noted in the range 38–46 mgPt/L. Taking into consideration PACl underdose conditions, too low a concentration of precipitates caused their inability to agglomerate. Raw water and clarified water turbidity was 5.6–8.1 NTU and 5.4–8.5 NTU, respectively. It was accompanied by an increase in the number of 1 μm particles by 25%. The removal of 10 μm particle number was only 18%–49%, indicating low flocculation effectiveness.

Coagulation with sludge recirculation

After 56 hours of conventional treatment, sludge recirculation to a flocculation chamber started up. Based on the analysis of Figure 4(a)–4(e), it can be concluded that, regardless of absorbance UV_{254} variations in raw water, sludge dosing clearly stabilized the coagulation process. Clarified water absorbance was lower than 3.4 m^{-1}. At the same time turbidity was reduced to 2–3 NTU, colour ranged from 17 to 28 mgPt/L, except for the first 20 hours of sludge dosing (76 hours after the system start-up). Such a long period was necessary for the required concentration of precipitates, susceptible to agglomeration, to be reached in the flocculation chamber. At the same time, the sorption properties of recycled and fresh precipitates were sufficient to adsorb dissolved organic compounds, resulting in the immediate high effectiveness of absorbance removal.

Sludge precipitates enhanced floc agglomeration and sedimentation of precipitated aggregates, contributing to a decrease of turbidity and the number of particles of 1 and 10 μm. An increase of 10 μm particle removal up to 80–93%, in comparison to 18–49% in conventional coagulation, proves that recycled sludge dosing enhanced flocculation. The removal of 1 μm particles confirms that coagulation with sludge recirculation was also effective. Because of variable raw water quality, periods of PACl underdosing and overdosing were occasionally reported. Periodical shortage of the coagulant dose was confirmed by daily jar tests. In relation to the optimal dose stated in jar testing, deficiency of the PACl dose used in the pilot study was up to 15%. The dose applied during treatment with recycled sludge in a pilot system was sometimes very close to the optimal PACl dose stated in jar testing without sludge dosing. However, no negative impact on treated water quality parameters was noted. To sum up, sludge precipitates may, to some extent, buffer the negative effects of too low or too high a PACl dose. It is particularly important during treatment of variable quality waters, e.g. mountain waters.

CONCLUSIONS

In treatment of waters characterized by low buffer capacity, low temperature and high variability of composition in short periods of time, it is very difficult to adjust a PACl dose to variations in water quality. The research results proved that recirculation of post-coagulation sludge into a flocculation tank is an effective method for maintaining high and stable coagulation effectiveness both in overdose and underdose conditions.

The reuse of post-coagulation sludge enables the enhancement of coagulation efficiency and reduction in the dose of coagulant in relation to conventional coagulation. This is due to the fact that sludge precipitates act as nuclei and still show unexploded sorption properties. On the other hand, sludge addition prevents the adverse effects of PACl overdosing that result in deterioration of filtration effectiveness.

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