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Performance evaluation of an inclined belt filter using coagulation/flocculation aids for the removal of suspended solids and phosphorus from microscreen backwash effluent☆

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Abstract

As environmental regulations become more stringent, environmentally sound waste management and disposal practices are increasingly more important in all types of aquaculture. In many recirculation systems, microscreen filters are used to remove and concentrate the suspended solids from the process water, because they require minimal labor and floor space and can treat large flow rates of water with little head loss. These microscreen filters generate a separate solids waste stream that can be further concentrated to reduce the quantity and improve the quality of discharge water. A Belt Filter System, Hydrotech Model HBF537-1H, from Waste Management Technologies Inc., Baton Rouge, LA, USA was evaluated for rapid thickening of sludge from the backwash water of a microscreen filter. When used in conjunction with coagulation/flocculation aids, significant reduction of suspended solid and phosphorus are possible. Testing of the system was conducted using the backwash effluent of a microscreen filter that treated water discharged from several large-scale recirculating aquaculture production systems growing artic char and trout. The system was tested using only alum as the coagulant aid, using only a commercially available polymer as the flocculation aid and the two coagulation/flocculation aids in combination.

Alum alone was moderately efficient in removing solids (82%), but was very efficient in sequestering reactive phosphorus (96%), with effluent concentrations less than 0.07 mg/L-P at the highest alum dosage tested, 100 mg/L. Several commercially available polymers used alone and at relatively low dosages (15 mg/L) were very effective in removing suspended solids, with a removal rate averaging 96% and with an effluent TSS concentration of less than 30 mg/L. The polymers were not as efficient as alum in removing reactive phosphorus, with a removal rate of approximately 40%. At the optimum combined dosage of alum (mg/L) and polymer (mg/L), the Inclined Belt Filter System increased the dry matter content of the sludge to approximately 13% solids, and reduced both the suspended solids and reactive phosphorus concentration of the effluent by 95 and 80%, respectively. The combination of coagulation/flocculation aids and the inclined belt filter show excellent potential to greatly reduce the volume of solids generated, and significantly reduce the concentration of suspended solids and phosphorus in discharged

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effluents. By eliminating the need for settling tanks or ponds, the leaching of nutrients (phosphorus, nitrogen) is minimized and the dewatered sludge is in a form for easy transport, storage, or disposal.

Keywords: Waste management; Belt filter; Coagulation aids; Flocculant aids

1. Introduction

As environmental regulations become more stringent, environmentally sound waste management and disposal are increasingly more important in all aquaculture operations. Two of the primary concerns are the suspended solids and phosphorus in the discharged effluent. In many recirculation systems, microscreen filters are used to remove and concentrate the suspended solids from the process water, because they require minimal labor and floor space and can treat large flow rates of water with little head loss (Cripps and Bergheim, 2000; Timmons et al., 2002). In addition, microscreen filters generate a separate solids waste stream that can be further concentrated to reduce the quantity and improve the quality of discharge water. In addition to suspended solids, phosphorus is one of the most scrutinized nutrients discharged by aquaculture systems, due to its potential for eutrophication of receiving waters. While some progress has been made in reducing the phosphorus content of feeds, few attempts have been made to reduce the phosphorus levels in the effluent water from intensive recirculating aquaculture systems. However, it has been shown that the majority of the phosphorus discharged from intensive aquaculture systems (50–85%) is contained in the filterable or settleable solids fraction (Bergheim et al., 1993; Heinen et al., 1996). Thus, any mechanism that could enhance solids removal would also contribute to a reduction in the overall level of phosphorus discharge. Because backwash from microscreen filters provides a concentrated waste stream, there are increased opportunities for more efficient and economical phosphorus control.

Over the past several years, the Conservation Funds Freshwater Institute has researched and demonstrated several technologies and strategies to manage and reduce the wastes generated during aquaculture production, including improved feed and feeding strategies (Tsukuda et al., 2000), technologies to minimize water use and concentrate waste streams (Timmons and Summerfelt, 1997; Summerfelt et al., 2000) and overall waste management and treatment reviews (Summerfelt, 1998; Summerfelt et al., 1999; Ebeling and Summerfelt, 2002). Using standard laboratory Jar tests, the application of several coagulation aids (alum and ferric chloride) for treating the supernatant from settling cones was investigated by Ebeling et al. (2003) and for backwash water from microscreen filters (Ebeling et al., 2004). In addition, a screening and evaluation of several commercially available polymers was conducted using laboratory Jar tests to determine their effectiveness as coagulation/flocculation aids for aquaculture effluents (Ebeling et al., 2005). Finally, a series of laboratory Jar tests were conducted to evaluate the effectiveness of using a combination of alum and a polymer (Rishel and Ebeling, 2005).

Inclined belt filters are one of the newest technologies to manage aquaculture effluent waste stream, and they have been specifically designed to thicken sludge from the backwash water of a microscreen filter. Testing of the Belt Filter System, Hydrotech Model HBF537-1H, from Waste Management Technologies Inc., Baton Rouge, LA, USA coagulation/flocculation system was conducted using the backwash effluent from several aquaculture production systems at the Conservation Funds Freshwater Institute in Shepherdstown, WV. Alum was used as the primary coagulation aid because it is readily availability in dry form and its ease of storage and mixing. A commercially available polymer was used as the flocculation aid. The coagulation/flocculation system was plumbed in to treat the waste discharge stream of a microscreen filter used as final treatment of discharge water from several large-scale recirculating aquaculture production systems growing arctic char and trout. The objectives of this research were to evaluate the effectiveness of the Belt Filter System for treating a recirculating system's microscreen backwash effluent and to determine the optimal dosage of alum and polymer used separately or in combination for the removal of suspended solids and phosphorus.

2. Coagulation and flocculation

One of the most commonly used methods for the removal of suspended solids in drinking water is the addition of coagulant and flocculation aids, such as alum and long chain polymers (AWWA, 1997). Coagulation is the process of decreasing or neutralizing the electric charge on suspended particles or zeta potential. Like electric charges on small particles in water cause them to naturally repel each other and hold the small, colloidal particles apart, keeping them in suspension. The coagulation/flocculation process neutralizes or reduces the negative charge on these particles, which then allows the van der Waals force of attraction to encourage initial aggregation of colloidal and fine suspended materials to form microfloc. Flocculation is the process of bringing together the microfloc particles to form large agglomerations by physically mixing or through the binding action of flocculants, such as long chain polymers.

2.1. Alum

Aluminum sulfate (alum) is the most commonly used coagulant and is easy to handle, store, mix, and apply. When alum is added to a wastewater, the following reaction takes place (Metcalf and Eddy, 1991):

$$Al_2(SO_4)_3{\cdot}18H_2O + 3Ca(HCO_3)_2 \Leftrightarrow 3CaSO_4 + 2Al(OH)_3 + 6CO_2 + 18H_2O \quad (1)$$

The insoluble aluminum hydroxide, $Al(OH)_3$, is a gelatinous floc that settles slowly through the wastewater, sweeping out the suspended material. As can be seen from the reaction, alkalinity is required for its completion and if not available must be added at the rate of 0.45 mg/L as $CaCO_3$ for every 1.0 mg/L alum.

In addition, aluminum salts can also be used for the chemical precipitation of phosphorus. The basic reaction involved is (Metcalf and Eddy, 1991):

$$Al^{3+} + PO_4{}^{3-} \Leftrightarrow AlPO_4 \quad (2)$$

The above equation is the simplest forms of the reaction (Metcalf and Eddy, 1991; Lee and Lin, 2000). Due to the many other competing reactions, the effects of alkalinity, pH, trace elements, and other compounds in the wastewater, the actual chemical dosage required to remove a given quantity of phosphorus is usually established on the basis of bench-scale test or sometimes pilot-scale tests. Previous bench top work (Ebeling et al., 2004) establishes that alum dosages of 60 mg/L would be most effective at removing TSS and phosphorus from backwash of microscreen filters.

2.2. Polymers

Recently, high molecular weight long-chain polymers have been used as a replacement for or in addition to alum for the coagulation of suspended solids (Ebeling et al., 2005). Advantages of using polymers alone are that lower dosages are required and smaller quantities of sludge are produced. In addition, both the molecular weight and charge densities can be optimized creating ‘‘designer’’ coagulation/flocculant aids. Polymers or polyelectrolytes consist of simple monomers that are polymerized into high-molecular-weight substances (Metcalf and Eddy, 1991) with molecular weights varying from 10^4 to 10^6 Da. Polymers can vary in molecular weight, structure (linear versus branched), amount of charge, charge type and composition. The intensity of the charge depends upon the degree of ionization of the functional groups, the degree of copolymerization and/or the amount of substituted groups in the polymer structure (Wakeman and Tarleton, 1999). With respect to charge, organic polymers can be cationic (positively charged), anionic (negatively charged) or nonionic (no charge). Polymers in solution generally exhibit low diffusion rates and raised viscosities, thus it is necessary to mechanically disperse the polymer into the water. This is accomplished with short, vigorous mixing to maximize dispersion, but not so vigorous as to degrade the polymer or the flocs as they form (Wakeman and Tarleton, 1999).

The effectiveness of high molecular weight long-chain polymer treatment of aquaculture wastewater depends on the polymer concentration, charge (anionic, cationic, and nonionic), molecular weight, and charge density (Ebeling et al., 2005). Polyelectrolytes act in two distinct ways: charge neutralization and bridging between particles. As wastewater particles are normally charged negatively, low molecular weight cationic polyelectrolytes can act as a coagulant, similar to alum, which neutralizes or reduces the negative charge on the particles. This has the effect of drastically reducing the repulsive force between colloidal particles, which allows the van der Waals force of attraction to encourage initial aggregation of colloidal and fine suspended materials to form microfloc. The coagulated particles are extremely dense, tend to pack closely, and settle rapidly. If too much polymer is used, however, a charge reversal can occur and the particles will again become dispersed, but with a positive charge rather than negatively charged.

Higher molecular weight polymers are generally used to promote bridging flocculation. The long chain polymers attach at a relatively few sites on the particles, leaving long loops and tails which stretch out into the surrounding water. In order for the bridging flocculants to work, the distance between the particles must be small enough for the loops and tails to connect two particles. The polymer molecule thus attaches itself to another particle forming a bridge. Flocculation is usually more effective the higher the molecular weight of the polymer. If too much polymer is used however, the entire particle surface can become coated with polymer, such that no sites are available to "bridge" with other particles. In general, high molecular weight polymers produce relatively large, loosely packed flocs, and more fragile flocs (Wakeman and Tarleton, 1999).

3. Materials and methods

3.1. Initial evaluation using Jar tests

As the chemistry of wastewater has a significant effect on the performance of a polymer, as well as alum, the selection of a type of polymer and dosage generally requires testing with the targeted waste stream and the final selection is often more of an "art" than a science. Hundreds of polymers are available from numerous manufactures with a wide variety of physical and chemical properties. And, although the manufactures can often help in a general way, the end user must often determine from all the various product lines which is best for their particular application and waste stream.

Since coagulant/flocculant interactions are very complex, laboratory studies, i.e. Jar tests, are used to determine the optimal dosage, duration, and intensity of mixing and flocculation. The coagulation–flocculation process consists of three distinct steps. First, the coagulant is added to the effluent water and a rapid and moderately intensity mixing is initiated. The objective is to obtain complete mixing of the coagulant with the wastewater to maximize the effectiveness of destabilization of colloidal particles and initiate coagulation. Second, the polymer is added and intensive mixing is used to completely disperse the polymer through out the effluent water. Third, the suspension is slowly stirred to increase contact between coagulating particles and to facilitate the development of large flocs via the polymer. Again, the flocculation duration and intensity are critical parameters. As for example too high intensity can break up the aggregate floc.

A standard Jar test apparatus, the Phipps & Bird Six-Paddle Stirrer with Illuminated Base was employed for the initial screening tests, with six 2 L^2 B-Ker^2 Plexiglas Jars. The jars are provided with a sampling port, 10 cm below the water line, which allows for repetitive sampling with minimal impact on the test. The six flat paddles are all driven by a single variable speed motor from 0 to 300 rpm. An illuminated base helps observation of the floc formation and settling characteristics. For additional information on the Jar test procedure, see Ebeling et al. (2004); Ebeling et al. (2005); Rishel and Ebeling (2005).

A series of Jar tests were carried out with alum to determine the dosages and conditions (mixing and flocculation stirring speeds, durations, and settling times) required to achieve optimum waste capture (ASTM, 1995; Ebeling et al., 2004). Optimum suspended solids removal was achieved with a 60 mg/L dosage of alum, reducing TSS from an initial influent value of approximately 320 mg/L to an effluent of approximately 10 mg/L. In addition, at a dosage of 60 mg/L, the reactive phosphorus removal efficiency for alum was greater than 90%. Flocculation and mixing speed and duration played only a minor role in the removal efficiencies for both orthophosphates and suspended solids. Both coagulation–flocculation aids also exhibited excellent settling characteristics, with the majority of the floc quickly settling out in the first 5 min.

In addition, a series of Jar tests were conducted to screen a wide range of commercially available polymers and evaluate the performance of a small subset which showed potential for use with aquaculture microscreen backwash effluent (Ebeling et al., 2005). Although a wide range of types of polymers were used, the results show excellent removal efficiencies for all of them with suspended solids removal close to 99% and a final TSS values ranging from as low as 10 to 17 mg/L. Although polymers are not intended to be used for phosphorus removal, reactive phosphorus was reduced by 92–95% by removing most of the TSS in the wastewater.

Finally, a series of Jar tests using both alum and a polymer were conducted to determine the dosages required to achieve optimum removal for both suspended solids and reactive phosphorus (Rishel and Ebeling, 2005). With several different alum/polymer combinations, i.e. 50 mg/L alum and 5 mg/L cationic polyacrylamide polymer, percent removal rates were as high as 99% for suspended solids, reactive phosphorus, and total phosphorus. With final concentrations of suspended solids less than 10 mg/L, reactive phosphorus less than 0.30 mg/L-P and total phosphorus less than 1.5 mg/L-P.

3.2. Water quality

The waste stream for treatment was taken directly from the holding tanks receiving the backwash water from several rotating microscreen filters used for suspended solids removal in two commercial size recirculating production systems growing arctic charr and trout. The first of these is a pilot-scale partial-reuse system consisting of three 3.66 m × 1.1 m deep circular 'Cornell-type' dual-drain culture tanks with a maximum feed loading rate of 45–50 kg of feed per day (Summerfelt et al., 2004a). The second system is a fully recirculating system consisting of a 150 m^3 circular production tank with a maximum daily feed rate of 200 kg of feed per day (Summerfelt et al., 2004b). Water quality characteristics of the microscreen backwash effluent are summarized in Table 1. Because of the excess alkalinity of the spring water at this location, no alkalinity additions were required in conjunction with alum treatment.

Table 1
Water quality characteristics of the microscreen backwash effluent (influent to belt filter)

Parameter		Mean	S.D.	Range
pH		7.43	0.26	6.97–7.78
Temperature	(°C)	19.4	1.4	18–21
Alkalinity	(mg/L)	292	21	260–324
RP	(mg/L-P)	4.0	1.9	1.9–7.2
TP	(mg/L-P)	77.8	7.8	23–192
TSS	(mg/L)	1015	401	517–1540
TN	(mg/L-N)	77.8	89.6	8–236
TAN	(mg/L-N)	14.8	24.5	3.4–92
NO_2	(mg/L-N)	0.43	0.34	0.23–1.36
NO_3	(mg/L-N)	38.8	9.2	25.5–48.6
$cBOD_5$	(mg/L)	402	138	195–642

For all of the belt filter tests, pH, alkalinity, turbidity, total suspended solids (TSS) and reactive phosphorus (RP, orthophosphate) were measured for the influent and effluent waste water streams. Samples were filtered through a 1.2 μm glass microfiber filter (Whitman, Maidstone, Kent, UK) with the filtrate then used to determine dissolved constituent concentrations. Sludge samples were analyzed for percent solids. Grab samples were taken of the inlet waste stream, the effluent from the Belt Filter System, the solids from the scraper bar and an overnight composite sludge sample from the sludge collection bucket. In addition, for several tests, total phosphorus, total nitrogen, $cBOD_5$, and COD were analyzed. For the purpose of comparing the effect of various operating parameters such as alum or polymer dosage, turbidity in addition to TSS was used as an indicator of suspended solids and reactive phosphorus for phosphorus content. Table 2 shows the methods used for each analysis. When appropriate, reagent standards and blanks were analyzed along with the samples to ensure quality control. The comparison treatments were statistically analyzed using a single factor ANOVA test with Microsoft Excel and two-sample *t*-test using Sigma Plot at a significance level of $\alpha = 0.05$.

3.3. Hydrotech Belt Filter System

The Hydrotech Belt Filter, Model HBF537-1H (Fig. 1) was purchased from Water Management Technologies Inc. (Baton Rouge, LA, http://www.W-M-T.com). The system consisted of two parts, a

Table 2
Laboratory methods used for analysis via titration or a Hach DR/2500 colorimeter

Parameter	Method/range
Alkalinity[a]	Standard Methods 2320B
Phosphorus, reactive[b]	Hach Method 8048 (Orthophosphate) 0–0.8 mg/L-P
Total suspended solids[a]	Standard Methods 2540D
Turbidity[a]	Hach Method 8237 0–450 NTU (Nephelometric Turbidity Units)
Total phosphorus[b]	Hach Method 8190 (Acid Persulfate Digestion) 0.00–3.50 mg/L PO_4^{3-}
Total nitrogen[a]	Hach Method 10072 (Acid Persulfate Digestion) 10–150 mg/L-N
$cBOD_5$	Standard Methods 5210
COD[b]	Hach Method 8000 (Potassium Dichromate Oxidation Method)

[a] Adapted from Standard Methods for the Examination of Water and Wastewater (APHA, 1989).
[b] USEPA approved for reporting.

mixing/flocculation tank and an inclined belt filter. The mixing tank was separated into four chambers, three with an approximate volume of 0.28 m^3 and one at 0.02 m^3. Total volume of the tank was 0.83 m^3 (Fig. 2). The first and last chambers had variable speed mixing impellers for slow mixing and the smaller, intermediate chamber had a fixed, 10 cm diameter, high-speed (1080 rpm) impeller for polymer mixing. As the waste stream enters the first chamber, alum was injected with a variable speed, peristaltic pump (Masterflex pump, Model 7524-40) from a reservoir at a dosing rate of 0, 25, 50 75 and 100 mg alum per liter of waste stream influent. This was accomplished by mixing a concentrated solution of alum, 2000 g alum in 20 L of spring water and with a waste stream flow rate of 40 L/m, dosing the waste stream at a rate of 0, 10, 20, 30, and 40 mL/min of alum solution. The 34 cm diameter impeller mixed the alum at 60 rpm with the wastewater stream and began the coagulation process. The fine particles in the wastewater stream were charge neutralized and began to aggregate into small floc. The wastewater stream then flowed over a weir into the smaller chamber, where polymer was injected at the surface, again using a variable speed peristaltic pump from a reservoir at polymer dosages of 0, 5, 10, 15, 20, and 25 mg polymer per liter of waste stream influent. The polymer used, Hyperfloc CE 1950 was from Hychem Inc., Tampa, Fl, USA (http://www.hydchem.com), a high degree of cationic charge, very high molecular weight polyacrylamide. The concentrated polymer was first diluted to approximately 0.2% or 2 g polymer in L of spring water, activated by mixing at high speed, and stored in a polyethylene reservoir. At this concentration, the polymer can be stored for about 24–48 h. A Masterflex pump, Model 7524-40 was used to accurately meter

Fig. 1. The Hydrotech Belt Filter System, consisting of a coagulation/flocculation tank (left) and an inclined belt filter (right).

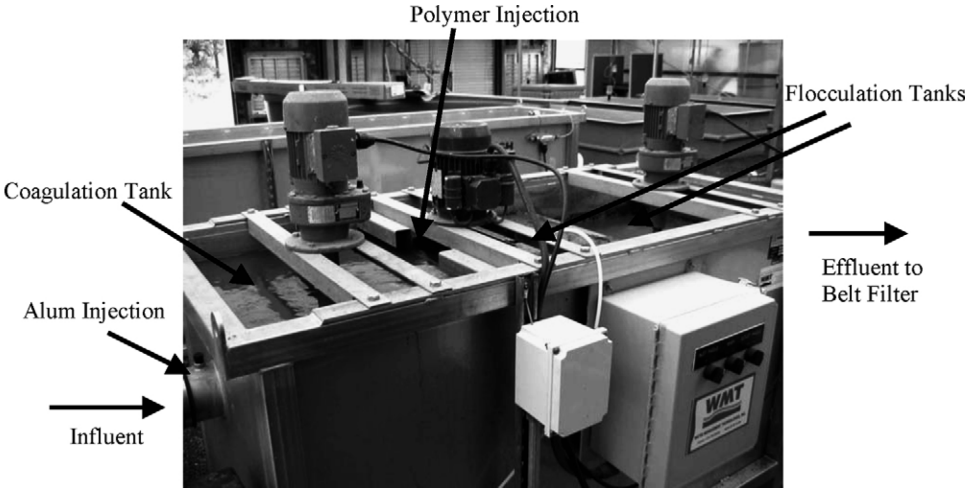

Fig. 2. The coagulation/flocculation tank with two variable speed mixers and one fixed speed polymer mixer and mixers control panel.

the required dose. A 1080 rpm, fixed speed impeller than mechanically mixes the polymer into the waste stream with a short, vigorous mixing to maximize dispersion of the polymer and forced the wastewater stream down and into the third chamber. There the polymer began the process of aggregation of the small particles and floc. Finally, the wastewater stream flowed over a weir into the fourth chamber, where a 34 cm diameter impeller at 60 rpm helped flocculate the floc particles into large floc and maintain them in suspension. From here, the waste stream consisting of large floc particles and relatively clear filtrate flowed into the belt filter header box through a 10 cm pipe.

The continuous belt of the inclined belt filter was made of polyester cloth with a mesh size of approximately 120 μm and an angled inclination slope of 10°. As the waste stream flowed onto the belt, the filtrate filters through into the lower sump, and as the belt slowly becomes blocked by sludge, the headloss across the belt filter increases until a level sensor activated a motor which starts the endless band moving. The inclined belt filter then gently lifted the floc out of the water and transported it to the end of the belt where it was scraped off of the belt by means of a firm rubber scraper (Fig. 3). A wash water jet spray system then cleaned the belt before it rotates back to the inlet end. During the test trials, the wash water was obtained from a separate clean water source, but could be obtained from the filtrate water in the lower sump. The belt wash water was routed back to the head of the microscreen for further processing. As the belt was self cleaning, belt maintenance was kept to a minimum. In this set-up, the clarified, treated wastewater stream flowed into a pump sump and to an aerobic wastewater treatment pond. The concentrated solids sludge were mixed with straw and as needed transported to a composite facility on site. In the event that the belt filter was unable to process all of the influent flow, a by-pass weir diverted the untreated waste stream back to the head of the microscreen filter.

During the research trials, the Belt Filter System was operated in a batch treatment mode. The backwash water from the microscreen filter accumulated in a 400 L HDPE equalization tank until filled, at which point it was pumped to the treatment process.

Fig. 3. Belt filter showing inlet weir box, floc, scraper bar and solids sump.

Filling time varied dependent on feed rates and management operations for the two recirculation systems, but usually was approximately 1 h. Event counters (Cutler-Hammer E42-2400 Totalizer) and interval timers (Cutler-Hammer E42-DI2475S Elapsed Timer) were installed on the microscreen filter, the sump pump in the equalization tank and the belt filter. These allowed determinations of the number of times the microscreen, the sump pump, and the belt filter turned on and how long they operated. A paddle-wheel flow meter (Signet Totalizer Model #3-5500) measured the total flow and the approximate rate of flow into the coagulation/flocculation tank. Combining the pump on-time and the total flow, allowed calculation of the actual average flow rate through the system.

A typical research trial consisted of setting the individual dosage rates for alum and the polymer, monitoring the system as the sump pump turned on, sampling influent, effluent flow and sludge from the scraper bar near the mid-point of the trial, and estimating effluent discharge rate with a bucket and stop watch. Typically four such trials were conducted per day and on average each dosage rate for alum and polymers were maintained for several days, yielding from 9 to 12 separate trials. Finally, an overnight sample was taken from the sludge collection bucket each morning for a composite percent solids analysis.

4. Results and discussion

4.1. Alum as the coagulation aid

Table 3 summarized the results of tests conducted at 0, 25, 50 75 and 100 mg/L alum dosages for on average of seven separate trials. A Single Factor ANOVA analysis showed no significant difference ($\alpha = 0.05$) for the influent pH and alkalinity of the waste stream, but as can be seen from the table there was an almost consistent linear decline in effluent pH and alkalinity as the dosage rate increased. As previously stated, alkalinity is required for the alum reaction and if not available must be added at the rate of 0.45 mg/L as $CaCO_3$ for every 1.0 mg/L alum. Although not as apparent at the lower dosage rates, the calculated drop in alkalinity at 100 mg/L alum should be about 45 mg/L, the measured average difference was 46 mg/L. Although not critical for this particular waste stream, if the waste stream alkalinity were substantially lower, then at the higher alum dosage rates some form of alkalinity would have to be added to facilitate this chemical reaction.

Fig. 4 shows the influent and effluent suspended solids concentration. A Single Factor ANOVA analysis showed no significant difference ($\alpha = 0.05$) for the influent suspended solids concentration, due to the large variation in concentrations tested. This was due to the impact of varying operational and management procedures used during the several months of testing, including cleaning, changes in feed rates, harvesting and research tasks. Overall suspended solids removal was not as high as expected based on the Jar tests, with no significant difference between the control and a dosage of 25 mg/L alum. There was a significant difference between the higher alum concentrations, 50, 75 and 100 mg/L, and the control and 25 mg/l alum. The reduced removal rate at high concentrations could be due to the effect of over dosing. Where because of the excess dosage, the alum does not just neutralize the negative charges on the particulates, but actually adds a net positive charge, creating the same repulsive tendencies between particles as in the initial conditions. Overall, the percent removal of suspended solids for both the control and at 25 mg/L was approximately 82% of the influent TSS concentration.

In addition to suspended solids removal, the prime reason for using alum was its sequestering of reactive phosphorus concentration as shown in Eq. (2). Fig. 5 shows the impact of alum on the reactive phosphorus concentration. A Single Factor ANOVA analysis indicated no significant difference ($\alpha = 0.05$) for the influent reactive phosphorus concentration, but as can be seen from Fig. 5, a significant impact on the effluent concentration. Even at the lowest alum dosage of 25 mg/L, 71% of the reactive phosphorus was removed and 96% at the highest dosage tested, 100 mg/L alum. Thus, alum demonstrated an excellent job of sequestering reactive phosphorus.

Finally, Fig. 6 shows the relationship between the influent suspended solids concentration and the performance of alum in removing reactive phosphorus. Because of different operating procedures, feed rates, harvesting operations, and mixing of the two sources of microscreen backwash effluent, the

Table 3
Impact of the Hydrotech Belt Filter System on water quality with alum as coagulation aid (number of samples)

Alum dosage		pH		Alkalinity (mg/L)		Turbidity (NTU)		TSS (mg/L)		RP[a] (mg/L-P)	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
0 mg/L	Influent	7.37	0.08	286	4	541	188	1128	534	1.59	0.50
(11)	Effluent	7.39	0.10	287	4	139	39	180	33	0.95	0.14
	%Removal			0%		73%		82%		38%	
25 mg/L	Influent	7.32	0.05	303	6	664	193	1363	768	1.76	0.77
(7)	Effluent	7.33	0.04	302	4	149	19	208	34	0.44	0.04
	%Removal			1%		76%		83%		71%	
50 mg/L	Influent	7.29	0.10	283	6	673	172	1451	509	1.51	0.36
(7)	Effluent	7.24	0.03	270	10	247	52	355	122	0.25	0.07
	%Removal			4%		62%		75%		82%	
75 mg/L	Influent	7.29	0.13	292	6	650	239	1318	527	1.87	0.57
(7)	Effluent	7.19	0.05	274	14	215	15	319	21	0.12	0.05
	%Removal			6%		63%		72%		93%	
100 mg/L	Influent	7.30	0.07	288	5	689	237	1682	635	1.78	0.48
(7)	Effluent	7.06	0.04	242	6	205	27	318	31	0.07	0.03
	%Removal			16%		68%		79%		96%	

[a] Reactive phosphorus.

effluent TSS ranged from as low as 500 mg/L to as high as 2500 mg/L. Fig. 6 shows that for the control with no coagulation/flocculation aid, the effluent reactive phosphorus was relatively constant at about 0.95 mg/L-P with a S.D. of 0.14 mg/L over the full range of influent TSS concentrations. This was not expected and suggests a constant value of soluble reactive phosphorus over the entire range of influent TSS. As a result of this constant influent reactive phosphorus concentration, the final concentration of the effluent reactive phosphorus remained relative constant across a wide range of influent TSS, declining as the alum concentration was increased. The implications of this are that a constant alum dosage

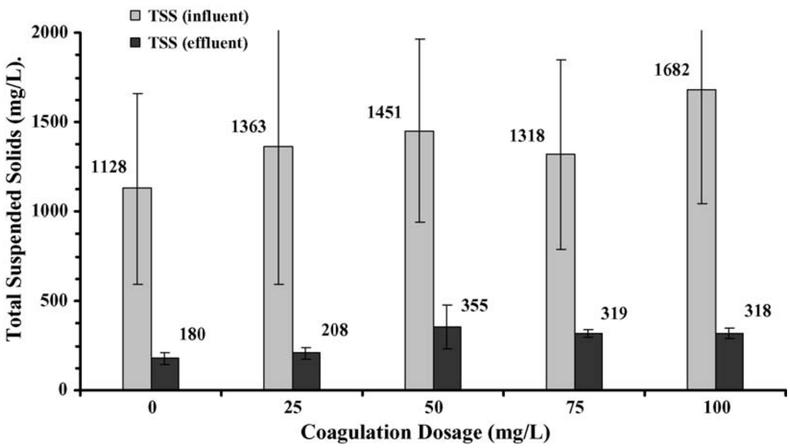

Fig. 4. Total suspended solids for the influent from the microscreen backwash sump and effluent from the belt filter as a function of alum dosage (mg/L).

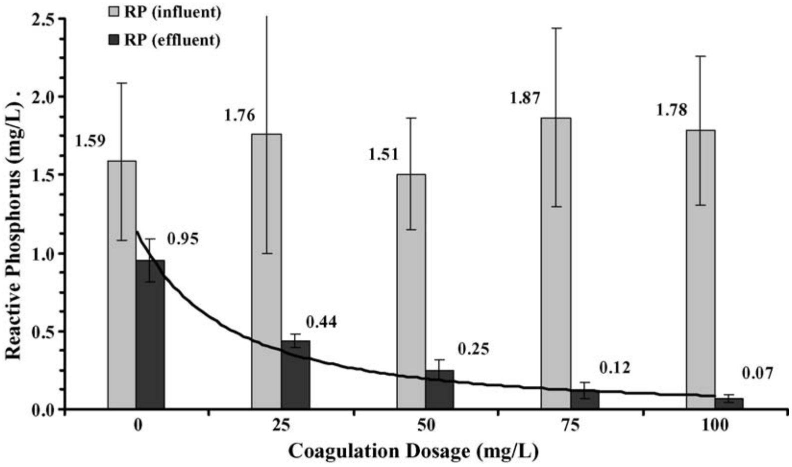

Fig. 5. Reactive phosphorus for the influent from the microscreen backwash sump and effluent from the belt filter as a function of alum dosage (mg/L).

will be effective over a wide range of influent TSS concentrations for the removal of reactive phosphorus. And for reactive phosphorus removal, the required alum dosage will be determined by the effluent concentration of reactive phosphorus required, based on environmental factors of the receiving system.

The average percent solids of the sludge scraped off of the belt by the scrapper bar was 13.2% with a S.D. of 1.1%. This would represent the maximum obtainable from the system, because some of the wash water tends to drain into the solids sump and reduce the overnight composite samples to as low as 5% solids, although this was significantly improved during later test runs. By adding a simple drainage system in the sludge sump, the final percent solids could be substantially improved to 10% solids or higher. It needs to be noted that the final sludge concentration will be, to some extent, dictated by how the sludge is handled or processed, for example, pumped or augured, stored over winter, composted or land applied.

4.2. Polymer as the coagulation and flocculant aid

Table 4 summarized the results of the polymer tests conducted at 0, 5, 10, 15, 20, and 25 mg/L polymer

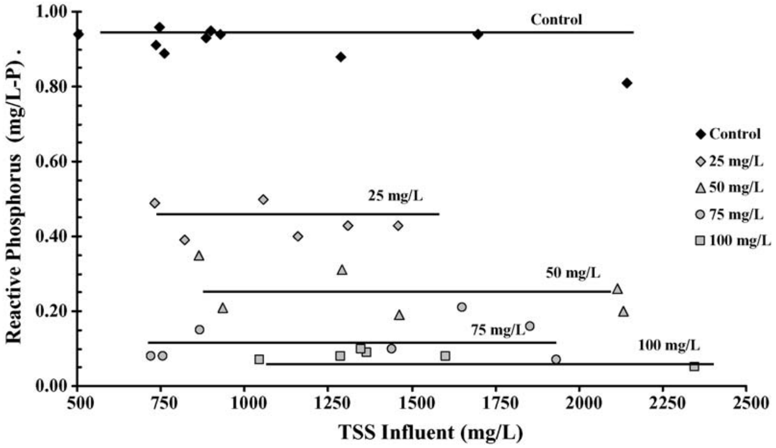

Fig. 6. Reactive phosphorus for the effluent from the belt filter as a function of total suspended solids of the influent (mg/L).

Table 4
Impact of the Hydrotech Belt Filter System on water quality with a polymer, Hychem, CE 1950, as coagulation/flocculation aid (number of samples)

Polymer dosage		pH		Turbidity (NTU)		TSS (mg/L)		RP[a] (mg/L-P)	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
0 mg/L	Influent	7.55	0.07	471	138	922	297	1.33	0.18
(12)	Effluent	7.62	0.08	147	22	200	55	1.02	0.13
	%Removal			66%		76.1%		23%	
5 mg/L	Influent	7.52	0.08	528	238	978	428	1.20	0.36
(8)	Effluent	7.55	0.09	65	35	104	60	0.85	0.31
	%Removal			87%		88.6%		26%	
10 mg/L	Influent	7.44	0.07	620	64	1165	316	1.34	0.44
(8)	Effluent	7.41	0.06	31	11	59	16	0.85	0.29
	%Removal			95%		94.7%		41%	
15 mg/L	Influent	7.45	0.08	570	85	1002	223	1.57	0.38
(14)	Effluent	7.31	0.08	23	6	39	12	1.38	0.36
	%Removal			96%		96.0%		14%	
20 mg/L	Influent	7.47	0.07	613	124	1201	548	1.79	0.36
(12)	Effluent	7.39	0.10	18	9	30	13	1.22	0.46
	%Removal			97%		97.3%		32%	
25 mg/L	Influent	7.42	0.05	516	30	745	69	1.36	0.20
(8)	Effluent	7.31	0.13	13	9	27	17	0.81	0.21
	%Removal			97%		96.3%		39%	

[a] Reactive phosphorus.

dosages for from 8 to 12 separate trials. Since there are no chemical reactions involved with the use of polymers, there should be no effect on pH or alkalinity and indeed this was seen with no significant difference in the means of the research trials pH with a paired *t*-test at $\alpha = 0.05$. As with the previous tests with alum, there was no significant difference in the influent TSS concentrations. There was, however, a significant impact on the effluent turbidity and TSS (Fig. 7). More importantly, there was no significant difference in the

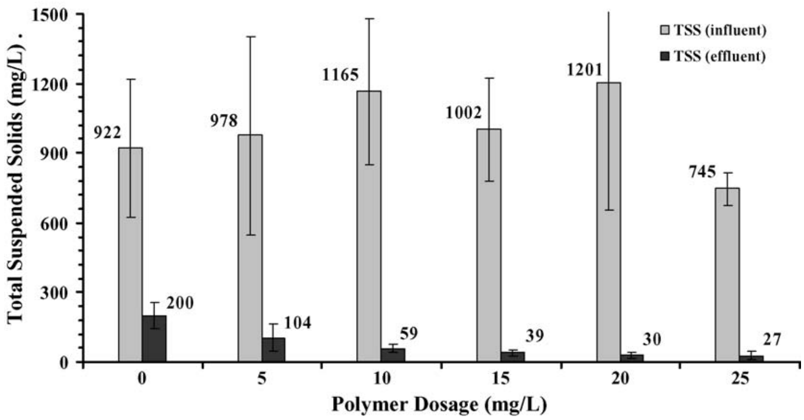

Fig. 7. Total suspended solids for the influent from the microscreen backwash sump and effluent from the belt filter as a function of polymer dosage (mg/L).

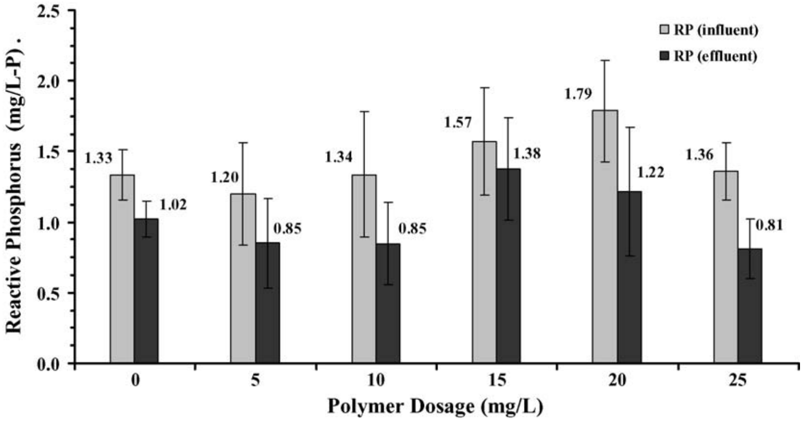

Fig. 8. Reactive phosphorus for the influent from the microscreen backwash sump and effluent from the belt filter as a function of polymer dosage (mg/L).

highest three polymer dosages (15, 20 and 25 mg/L) with percent removal of TSS averaging approximately 96%, with an effluent TSS concentration of less than 30 mg/L. Thus, polymer used alone and at concentrations of 10–15 mg/L was very efficient in removing suspended solids.

Fig. 8 shows the removal of reactive phosphorus from the microscreen backwash effluent as a function of the polymer dosage. Except for the 15 mg/L dosage, there was no significant difference between the treatments in percent removal. Although the reactive phosphorus percent removal was lower than seen with the Jar test evaluations, the final concentration was approximately the same at about 1.0 mg/L-P. It should be remembered that unlike alum, polymers are not intended for reactive phosphorus removal except by flocculating out small particles.

Finally, Fig. 9 shows the impact of influent suspended solids concentration on the performance of the polymer. Again because of different operating procedures, feed rates, harvesting operations, etc. the effluent TSS ranged from as low as 500 mg/L to as high as 2500 mg/L. Fig. 9 shows how for the control with no coagulation/flocculation aid, the effluent TSS was relatively constant at about 200 mg/L with a S.D. of 55 mg/L over the full range of influent TSS

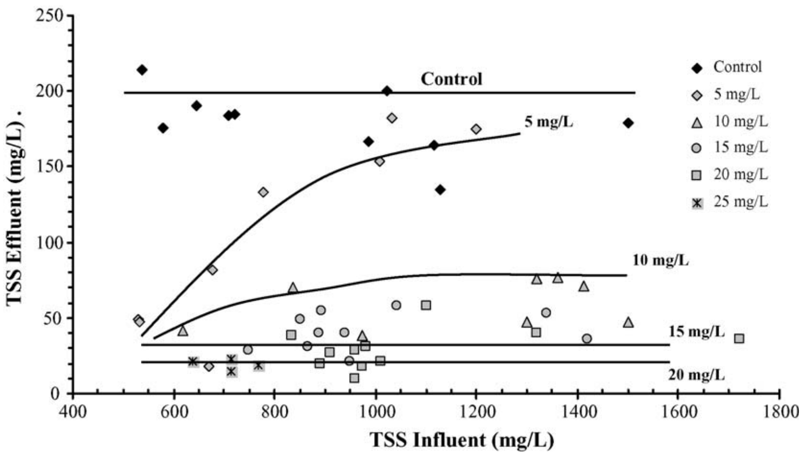

Fig. 9. Impact of the influent TSS concentration on the effluent TSS from the belt filter as a function of polymer dosage (mg/L).

concentrations. The 5 mg/L polymer dosage demonstrates nicely how the removal rate is a function of influent TSS concentration, where at low TSS there is adequate polymer for both charge neutralization of the particles and flocculation. But as the concentration increases, there is insufficient polymer to completely neutralize all the particles and the removal rate becomes almost equal to the control rate. Correspondently, as the polymer dosage increases, the removal rate improves, until at 10–15 mg/L, there is no significant difference between the effluent TSS. Thus, for a waste stream with a known and constant TSS value, a fixed dosage of polymer would be used, compared to higher dosage rate for widely varying influent TSS value.

The average percent solids of the sludge scraped off of the belt by the scrapper bar was 11.6% with a S.D. of 2.2%, slightly less than with alum alone as a coagulation aid. This would represent the maximum obtainable from the system because some of the wash water tends to drain into the solids sump, although this was substantially reduced by a slight equipment modification so that the overnight composite increased to 9.9% solids.

4.3. Alum and polymer as the coagulation and flocculant aid

Finally, both alum and polymer were used in combination. Previous Jar tests had shown that there was a significant reduction in the optimal polymer dosage, when used in combination with alum (Rishel and Ebeling, 2005). In some cases, the required polymer dosages were reduced by as much as a factor of 10, when used in combination with alum to achieve the same suspended solids removal. Based on the Jar tests for the polymer used, Hychem, CE 1950, two concentrations of polymer were tested, 2.5 and 5.0 mg/L. A series of tests were then conducted at alum dosages of 12.5, 25, and 50 mg/L and the results are tabulated in Table 5.

As can be seen from Table 5 and Fig. 10, there was a wide variation in the influent suspended solids concentration over the several weeks of the research trial. In terms of the percent removal of suspended solids, there was a significant difference between the treatments, with a synergetic effect of the combination of alum and polymer. As each was increased, the

Table 5
Impacts of the Hydrotech Belt Filter System on water quality with alum as coagulation aid and polymer (Hychem, CE 1950) as a flocculation aid (number of samples)

Alum/polymer dosage		pH		Alkalinity (mg/L)		Turbidity (NTU)		TSS (mg/L)		RP[a] (mg/L-P)	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
0 mg/L/	Influent	7.37	0.08	286	4	541	188	1128	534	1.59	0.50
0 mg/L	Effluent	7.39	0.10	287	4	139	39	195	58	0.95	0.14
(11)	%Removal					73%		81%		38%	
12.5 mg/L/	Influent	7.23	0.14	289	6	606	216	1120	396	1.81	0.73
2.5 mg/L	Effluent	7.26	0.08	289	8	58	27	110	36	0.67	0.11
(11)	%Removal					90%		90%		59%	
12.5 mg/L/	Influent	7.26	0.08	285	3	791	212	1600	526	1.97	0.52
5 mg/L	Effluent	7.22	0.14	289	4	43	19	81	29	0.82	0.32
(11)	%Removal					95%		94%		55%	
25 mg/L/	Influent	7.34	0.14	284	5	398	156	753	352	1.28	0.63
2.5 mg/L	Effluent	7.27	0.10	281	3	33	15	65	28	0.45	0.10
(18)	%Removal					92%		91%		57%	
25 mg/L /	Influent	7.30	0.16	286	6	414	113	753	140	1.39	0.70
5 mg/L	Effluent	7.13	0.03	284	2	26	8	53	20	0.42	0.04
(3)	%Removal					94%		93%		65%	
50 mg/L /	Influent	7.38	0.07	280	3	335	42	646	87	0.88	0.07
2.5 mg/L	Effluent	7.14	0.05	269	7	16	5	34	11	0.18	0.04
(13)	%Removal					95%		95%		80%	

[a] Reactive phosphorus.

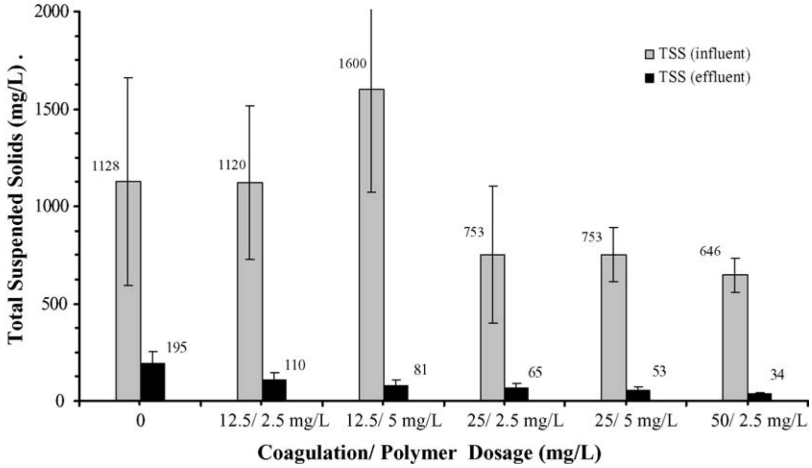

Fig. 10. Total suspended solids for the influent from the microscreen backwash sump and effluent from the belt filter as a function of coagulant (alum) and polymer (Hychem, CE 1950) dosage (mg/L).

suspended solids concentration decreased, with a final average concentration of only 34 mg/L or 95% removal at the highest combination tested. The important thing to note is that only 2.5 mg/L of Hychem, CE 1950 was used compared to 20 mg/L to achieve the same final suspended solids concentration using this polymer alone.

As was seen while using alum alone and from Fig. 10, alums impact on suspended solids removal was not as significant as that of the polymer. What was significant is its impact on reactive phosphorus concentration. As Fig. 11 shows, the concentration of reactive phosphorus steps down with each increase in alum, with no significant impact of the increase in polymer. Thus, there was no significant difference between the reactive phosphorus effluent concentration at the alum dosage of 12.5 and polymer dosages of 2.5 and 5.0 mg/L, between the alum dosage of 25 mg/

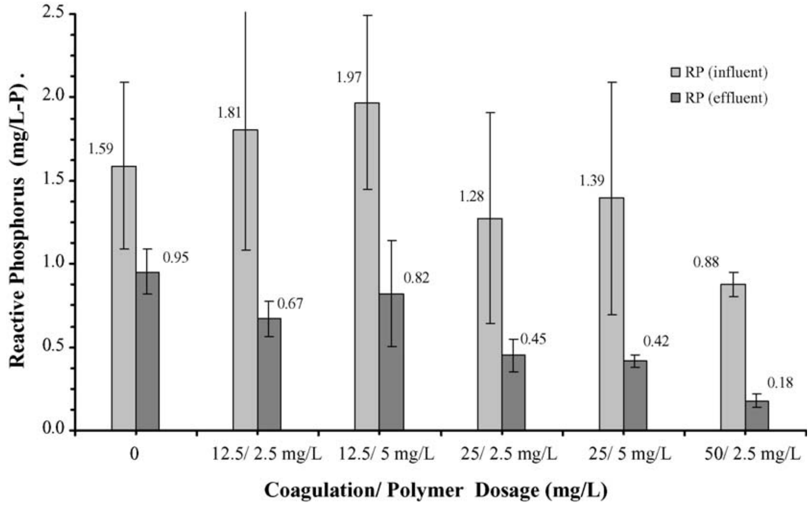

Fig. 11. Reactive phosphorus for the influent from the microscreen backwash sump and effluent from the belt filter as a function of coagulant (alum) and polymer (Hychem, CE 1950) dosage (mg/L).

Table 6
Impacts of the Hydrotech Belt Filter System on selected additional water quality parameters with alum as coagulation aid and polymer (Hychem, CE 1950) as a flocculation aid (on average number of samples)

Alum/polymer dosage		TP (mg/L-P)		TN (mg/L-N)		$cBOD_5$ (mg/L)		COD	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
12.5 mg/L/	Influent	95.1	39.9	49.1	20.6	498	89	–	–
2.5 mg/L	Effluent	12.2	2.6	8.5	3.8	227	24	–	–
(9)	%Removal	85%		81%		56%			
12.5 mg/L/	Influent	124	54	95	9.3	549	42	–	–
5 mg/L	Effluent	11.5	3.9	16.4	1.7	220	23	–	–
(3)	%Removal	90%		83%		60%			
25 mg/L/	Influent	71.7	49.1	36.2	19.8	359	214	758	162
2.5 mg/L	Effluent	7.2	3.2	4.7	1.1	81	17	112	14
(20)	%Removal	88%		83%		72%		85%	
25 mg/L/	Influent	62.3	25.3	37	19.8	–	–	880	140
5 mg/L	Effluent	5.9	1.6	6.3	2.3	–	–	87	22
(3)	%Removal	89%		83%				90%	
50 mg/L/	Influent	50.3	12.4	31.1	6.8	251	50	808	170
2.5 mg/L	Effluent	3.4	1.4	4.0	1.8	44	8	62	15
(9)	%Removal	93%		87%		82%		92%	

L and polymer dosages of 2.5 and 5.0 mg/L. There was, however, a significant difference between the three alum dosages, with the highest removal rate and lowest effluent concentration of reactive phosphorus at the highest dosage tested, 50 mg/L. In terms of percent removal of reactive phosphorus, there was no significant difference between all the treatments, except the last, 50 mg/L alum.

The average percent solids of the sludge scraped off of the belt by the scrapper bar was 12.6% with a S.D. of 1.4%, which was between the results using alum or polymer alone as a coagulation aid. This would represent the maximum obtainable from the system because some of the wash water tends to drain into the solids sump, although as previously mentioned this was substantially reduced by a slight equipment

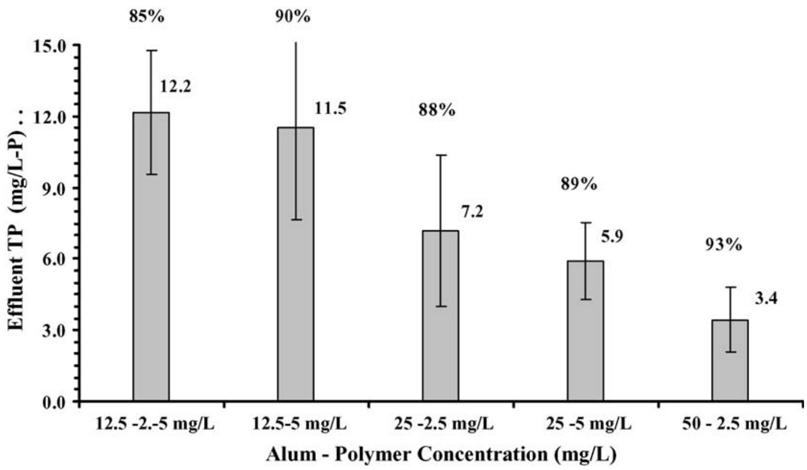

Fig. 12. Effluent total phosphorus from the belt filter and percent removal for the microscreen backwash wastewater as a function of coagulant (alum) and polymer (Hychem, CE 1950) dosage.

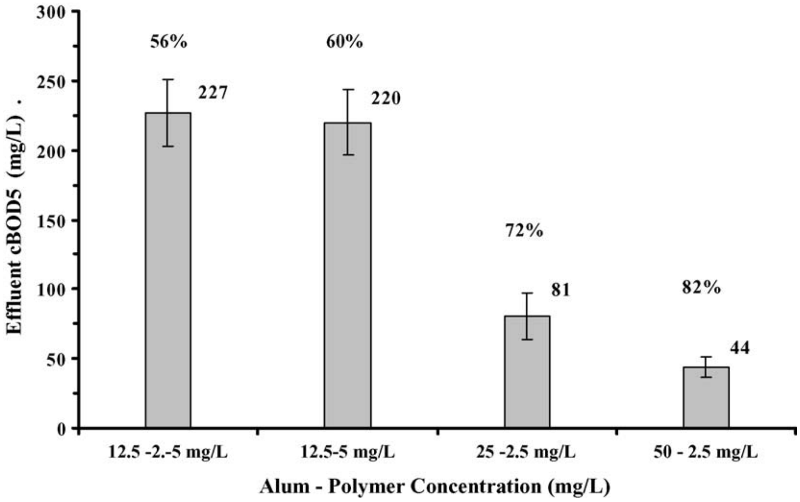

Fig. 13. Effluent $cBOD_5$ from the belt filter and percent removal for the microscreen backwash sump wastewater as a function of coagulant (alum) and polymer (Hychem, CE 1950) dosage (mg/L).

modification so that the overnight composite increased to 9.8% solids.

4.4. Other water quality parameters of interest

Although the suspended solids and reactive phosphorous in the discharged effluent was the primary focus of this research, several other parameters were evaluated for the combination of alum and polymer trials. These included total phosphorus, total nitrogen, $cBOD_5$, and COD, and are summarized in Table 6. The combination of alum and phosphorus significantly reduced the total phosphorus concentration in the effluent with a maximum removal efficiency of 93% and for several trials, a discharge concentration less than 2 mg/L-P. Fig. 12 shows how the effluent concentration of total phosphorus was not impacted by the polymer concentration, with no significant difference between the 2.5 and 5 mg/L polymer dosage at a fixed 12.5 mg/L alum dosage, but significant differences as the alum concentration increased. Although not intended for nitrogen removal, total nitrogen in the effluent was reduced by as much as 87% at the maximum dosage tested, with discharge concentrations for some trials of 2.1 mg/L. Fig. 13 shows the impact of the alum/polymer aids on $cBOD_5$, and again shows that alum played the most significant role. Removal rates for $cBOD_5$ were as high as 82%, with effluent concentrations as low as 35 mg/L. Finally, limited COD data also suggest corresponding reductions as high as 92%.

5. Conclusion

Alum used alone as a coagulant aid was not as efficient in removing solids (83%) as was expected based on Jar tests, but was very efficient in sequestering reactive phosphorus (96%), with effluent concentrations less than 0.07 mg/L-P at 100 mg/L alum. A cationic polymer used alone and at relatively low dosages (15 mg/L) was very efficient in removing suspended solids, with a removal rate averaging 96% and an effluent TSS concentration of less than 30 mg/L. At the optimum dosage of alum and polymer, the Hydrotech Belt Filter System increased the dry matter content of the sludge to approximately 12.6 % solids, and reduced both the suspended solids and soluble phosphorus concentration of the effluent by 95 and 80%, respectively. In addition, significant reductions in total phosphorus, total nitrogen, $cBOD_5$, and COD were seen. The combination of coagulation/flocculation aids and the Hydrotech Belt Filter System showed excellent potential to significantly reduce the volume of solids generated, and significantly reduce the concentration of suspended solids and phosphorus in discharged effluents. Even under the best conditions, the hydraulic loading rate was limited to approximately 40 Lpm per 0.5 m belt width. Future work includes additional research trials with other potential polymers, a courser belt sieve to increase hydraulic loading rate, and a closer examination and possible modification of the coagulation/flocculation system to improve it performance to match that obtained by laboratory Jar tests.

Acknowledgments

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References

APHA, 1989. Standard Methods for the Examination of Water and Wastewater, 17th ed. American Public Health Association, American Water Works Association, Water Pollution and Control Federation, Washington, D.C.

ASTM, 1995. Standard Practice for Coagulation–Flocculation Jar Test of Water E1-1994 R (1995). D 2035-80. Annual Book of ASTM Standards, vol. 11.02.

AWWA, 1997. Water treatment plant design, third ed. American Water Works Association, American Society of Civil Engineers, McGraw-Hill, New York.

Bergheim, A., Kristiansen, R., Kelly, L., 1993. Treatment and utilization of sludge from land-based farms for salmon. In: Wang, J.-K. (Ed.), Techniques for Modern Aquaculture. ASAE, St. Joseph, MI.

Cripps, S.J., Bergheim, A., 2000. Solids management and removal for intensive land-based aquaculture production systems. Aquacult. Eng. 22 (1), 33–56.

Ebeling, J.M., Summerfelt, S.T., 2002. Performance evaluation of a full-scale intensive recirculating aquaculture system's waste discharge treatment system. In: Rakestraw, T.T., Douglas, L.S., Flick, G.J. (Eds.), The Fourth International Conference on Recirculating Aquaculture, Virginia Polytechnic Institute and State University, Blacksburg, VA, pp. 506–515.

Ebeling, J.M., Sibrell, P.L., Ogden, S., Summerfelt, S.T., 2003. Evaluation of chemical coagulation–flocculation aids for the removal of phosphorus from recirculating aquaculture effluent. Aquacult. Eng. 29, 23–42.

Ebeling, J.M., Ogden, S., Sibrell, P.L., Rishel, K.L., 2004. Application of chemical coagulation aids for the removal of suspended solids and phosphorus from the microscreen effluent discharge of an intensive recirculating aquaculture system. J. North Am. Aquacult. 66, 198–207.

Ebeling, J.M., Rishel, K.L., Sibrell, P.L., 2005. Screening and evaluation of polymers as flocculation aids for the treatment of aquacultural effluents. Aquacult. Eng. 33 (4), 235–249.

Heinen, J.M., Hankins, J.A., Adler, P.R., 1996. Water quality and waste production in a recirculating trout culture system with feeding of a higher-energy or lower-energy diet. Aquacult. Res. 27, 699–710.

Lee, C.C., Lin, S.D., 2000. Handbook of Environmental Engineering Calculations. McGraw-Hill, New York.

Metcalf and Eddy Inc., 1991. Wastewater Engineering: Treatment, Disposal and Reuse, third ed. McGraw-Hill Inc., Boston, MA.

Rishel, K.L., Ebeling, J.M., 2005. Screening and evaluation of alum and polymer combinations as coagulation/flocculation aids to treatment of aquaculture effluents (in review).

Summerfelt, S.T., 1998. An integrated approach to aquaculture waste management in flowing water tank culture systems. In: Libey, G.S., Timmons, M.B. (Eds.), The Second International Conference on Recirculating Aquaculture, Virginia Polytechnic Institute and State University, Roanoke, VA, 16–19 July, pp. 87–97.

Summerfelt, S.T., Adler, P.R., Glenn, D.M., Kretschmann, R.N., 1999. Aquaculture sludge removal and stabilization within created wetlands. Aquacult. Eng. 19 (2), 81–92.

Summerfelt, S.T., Davidson, J., Timmons, M.B., 2000. Hydrodynamics in the 'Cornell-type' dual-drain tank. In: The Third International Conference on Recirculating Aquaculture, Virginia Polytechnic Institute and State University, Roanoke, VA, 22–23 July, pp. 160–166.

Summerfelt, S.T., Davidson, J.W., Waldrop, T.B., Tsukuda, S.M., Bebak-Williams, J., 2004a. A partial-reuse system for coldwater aquaculture. Aquacult. Eng. 31, 157–181.

Summerfelt, S.T., Wilton, G., Roberts, D., Savage, T., Fonkalsrud, K., 2004b. Developments in recirculating systems for Arctic char culture in North America. Aquacult. Eng. 30, 31–71.

Timmons, M.B., Summerfelt, S.T., 1997. Advances in circular culture tank engineering to enhance hydraulics, solids removal and fish management. In: Timmons, M.B., Losordo, T. (Eds.), Recent Advances in Aquacultural Engineering, November 9–12, Orlando, FL. Northeast Regional Agricultural Engineering Service, Ithaca, NY, pp. 66–84.

Timmons, M.B., Ebeling, J.M., Wheaton, F.W., Summerfelt, S.T., Vinci, B.J., 2002. Recirculating Aquaculture Systems, second ed. Cayuga Aqua Ventures, p. 769.

Tsukuda, S., Wallace, R., Summerfelt, S.T., Hankins, J., 2000. Development of a Third Generation acoustic waste feed monitor. In: The Third International Conference on Recirculating Aquaculture, Virginia Polytechnic Institute and State University, Roanoke, VA, 22–23 July, pp. 105–108.

Wakeman, R.J., Tarleton, E.S., 1999. FILTRATION: equipment selection, modeling, and process simulation. Elsevier Science Ltd., New York, pp. 446.