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A system for the treatment of sludge from land-based fish-farms

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Abstract – This paper describes both an experimental and a commercial-scale system for sludge dewatering and stabilisation. In the experimental system, back-wash water from rotating disk microsieves was settled in a conical sedimentation tank. This tank functioned well, commonly removing more than 75–80 % of the solids, at an overflow rate of 1.0–2.7 $m \cdot h^{-1}$. The hydraulic load was maintained low, so treatment efficiency was significantly positively influenced by inlet concentration and not inflow rate. Lime was added to the settled sludge. More than 99.9 % of the pathogenic viruses and bacteria studied were killed within 7 days at pH 12. In the commercial system, a newly developed combined effluent treatment and sludge processing system, was located in a large Norwegian salmon (*Salmo salar*) smolt farm. Four drum microsieves were used to separate particles from the primary effluent flow. The back-wash water, amounting to a maximum of 0.3 % of the 30–35 $m^3 \cdot min^{-1}$ primary flow, was dewatered using another drum microsieve. Dewatered back-wash water from this sieve was pumped to a sedimentation tank with a top surface area of 3.3 m^2 and a volume of 5.5 m^3. This system produced on average 0.7 L settled sludge containing ca. 10 % dry matter per kg of feed supplied. Sludge tapped from the bottom of the sedimentation tank was stabilised by mixing with lime. This system produced on average 0.7 L settled sludge containing ca. 10 % dry matter per kg of feed supplied. After stabilisation, the stored sludge was diluted with cattle manure and spread on agricultural land. The primary treated effluent was discharged into the receiving marine water body. The running costs of effluent and sludge treatment, including sieving, settling and stabilisation, amounted to US$ 0.056 per smolt produced, or about 5 % of the total production costs. In the recipient, no settled solids were detected on the seabed at the outlet point of the treated effluent. © Ifremer/Elsevier, Paris

Aquaculture / sludge / treatment efficiency / sludge quality / pathogens / fish-farms / microsieves / nitrogen / phosphorus

Résumé – Un système pour le traitement des boues rejetées par les fermes aquacoles. Cet article décrit deux systèmes de traitement de boues à échelle expérimentale et commerciale. Les boues sont essorées et stabilisées. Dans le système expérimental, les eaux de lavage des disques rotatifs de filtrage sédimentent dans un cylindre conique. Ce cylindre de sédimentation fonctionne correctement, retenant plus de 75 % des solides avec une surverse de 1,0 à 2,7 $m \cdot h^{-1}$. De la chaux a été ajoutée. Plus de 99,9 % des virus et bactéries pathogènes ont été tués en 7 jours à un pH de 12. Dans le nouveau système commercial, installé dans une ferme de production de smolts (*Salmo salar*), le traitement des effluents a été combiné avec le traitement des boues. Les eaux de lavage représentent 3 % du courant primaire de 30–35 $m^3 \cdot min^{-1}$; elles sont essorées en utilisant un filtre à tambour supplémentaire. Les eaux passant ce deuxième filtre sont envoyées dans un bassin de sédimentation d'une surperficie de 3,3 m^2 et d'un volume de 5,5 m^3. Les boues sont évacuées par le fond du bassin de sédimentation et stabilisées avec de la chaux. Ce système produit en moyenne 0,7 L de boue, avec environ 10 % de matières sèches par kilo d'aliment fourni. Après la stabilisation, la boue est mélangée avec du fumier de vache et répandue sur les champs. Les coûts de traitement reviennent à 0,056 US $ par smolt produit, soit environ 5 % du coût total de production. © Ifremer/Elsevier, Paris

Aquaculture / efficacité de traitement / qualité de boue / agents pathogènes / filtre / ferme d'élevage de poisson / azote / phosphore

1. INTRODUCTION

Since the early 1970s, methods and equipment have been developed to treat effluent wastewater from fish-farms. In modern flow-through farms with an outlet to freshwater, solids and nutrient loads are normally reduced by mechanical treatment. Most Norwegian hatcheries are however situated on the coast. The pol-

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lution control authorities in Norway have recently begun to require such farms to treat their effluents, if they discharge into marine areas with a limited recipient capacity.

There have been reviews of reported efficiencies of screens and sedimentation units used for primary treatment, such as that by Cripps and Kelly [4]. Unlike the primary treatment step, little attention has been paid to the development of methods for the further processing of the sludge produced in fish-farms. Unprocessed sludge is nevertheless dilute and has to be thickened, prior to utilisation, to increase the concentration several hundred to several thousand times [1]. Additionally, fresh sludge from fish-farms may contain fish pathogens, and is extremely susceptible to putrefaction. The sludge therefore has to be stabilised, which is a process of hygienisation and prevention of decomposition. The unrestricted use of untreated fish-farm sludge for spreading on agricultural land would otherwise present a potential risk of disease transfer to wild fish stocks and adjacent aquacultural installations. The first part of this paper (Experimental tests) describes sludge dewatering tests using a sedimentation tank. Lime was added to the settled sludge to investigate the efficiency with which it inactivated implanted pathogenic viruses and bacteria. In the second part of the article (Commercial-scale system), a description is given of the functioning of a newly developed, commercial-scale, combined effluent treatment and sludge processing system at a large Norwegian Atlantic salmon (*Salmo salar*) smolt farm.

2. MATERIAL AND METHODS

2.1. Experimental tests

All field tests were conducted at a commercial fish-farm, Bøvågen Fiskeoppdrett, which produces 1 million salmon smolts per year. Effluent particles were removed using a pair of proprietary microsieves (UNIK Canal Filters, mesh size 100 µm) continuously back-washed by freshwater jets. The dilute back-wash water was further processed in a pilot-scale sludge treatment system developed by UNIK Filtersystem, described as follows.

2.1.1. Thickening

A conical-bottomed sedimentation tank was used for particle settling. The volume of the upper cylindrical section of the unit was 1 000 L (diameter 1 200 mm), while that of the lower conical section for sludge removal was 400 L. The conical section sloped at an angle of 37° to a central, solids-collection point. A turbidity meter (model Hach), for the on-site control of outlet particle content and hence settling efficiency, was installed on the primary outlet pipe, located near the top of the tank.

The efficiency of the tank, in terms of outlet water turbidity, was tested three times throughout the year, at different effluent loading levels, during March, May and December 1995. Integrated samples, combined over two-hour periods, of inlet and primary outlet water from the settling tanks were collected during 18–36-h periods, once during each sampling month. The 1 L composite samples were collected using LIQUI-BOX automated water samplers, and stored at 4 °C until their return to the laboratory for analysis.

2.1.2. Sludge stabilisation

Settled sludge was collected from the sedimentation tank to determine the quantity of lime (CaO, 0–0.1 mm) and slaked lime ($Ca(OH)_2$, 0–0.1 mm) required to raise the pH to 12. Temperature and pH were continuously measured during lime addition and mixing.

2.1.3. Hygienisation trials

To study the hygienisation effect of the stabilisation process, lime treated and untreated sludges were inoculated with *Aeromonas salmonicida* and IPN-virus. In order to reach pH values of 11.0 and 12.0, 0.90 and 1.15 g $Ca(OH)_2$, respectively, were added in duplicate to 100 mL settled sludge with a dry matter content of 17.3 %. Sludge samples, prepared for *A. salmonicida* inoculation were heated to 80 °C for 2 min and cooled to 20 °C before lime addition, to eliminate interference from natural bacterial populations.

The experiments with *A. salmonicida* were conducted using a virulent strain, AL 2017 (strain collected by the Norwegian Institute of Fisheries and Aquaculture), which was originally isolated from Atlantic salmon (*Salmo salar*) after an outbreak of furunculosis in a Norwegian fish-farm. Agitated liquid cultures of bacteria were grown for 20 h at 22 °C in tryptone soy broth (Oxoid Ltd) supplemented with 0.5 % NaCl. Cells were harvested by centrifugation at 4 500 × *g* for 5 min and washed twice in a 0.9 % NaCl solution, before being mixed with the sludge to a density of 3 10^6 number of colony forming units (CFU) per mL.

The sludge samples were incubated at 20 °C with continuous stirring. Survival after selected time intervals was determined after neutralisation, serial dilutions in 0.9 % NaCl and spreading of appropriate samples on blood agar plates, in duplicate. Colonies were counted after 3 and 5 days of incubation in the dark at 22 °C.

Similar trials were repeated with the addition of IPN virus to lime treated and untreated sludges. After inoculation, duplicate sludge samples were agitated at 15 °C for selected time intervals. The virus was propagated and assayed in BF-2 tissue culture cells. Assays were conducted by observing cytopathic effects in monolayers on microtitre plate-wells after incubation with virus dilutions. The virus titre of samples was determined and reported as $TCID_{50} \cdot mL^{-1}$ (tissue culture 50 % ineffective dose per mL) after seven days of incubation.

2.2. Commercial-scale system

Stolt Sea Farm Norway's hatchery in Fjon is one of Norway's largest smolt farms with an annual production of about 1.5 million Atlantic salmon and rainbow trout (*Oncorhynchus mykiss*) fry, fingerlings and smolt. In 1996, the biomass production was 106 Mt at a feed conversion ratio (FCR) of 1.07 (kg feed·kg^{-1} weight gain). This high feed utilisation, combined with a high average water consumption of 30–35 $m^3 \cdot min^{-1}$, were the main reasons for the low effluent particle and nutrient concentrations. Oxygen was only added to the culture water in August–September when the biomass and temperatures were high.

A combined effluent treatment and sludge processing system was developed by Sterner Aquatech Ltd and built at the hatchery. This system (*figure 1*) together with preliminary test results, has been described [2].

Four intermittently back-washed rotary drum microsieves (Hydrotech), with 80–100 μm pore size screens, were used to separate particles from the primary effluent from the farm. The back-wash water, amounting to a maximum of 0.3 % of the primary flow volume, was dewatered using a further sieve of the same type, but with a 80-μm diameter pore size.

The treatment efficiency (TE) of the drum-sieves was calculated from frequent sampling of effluent water before (Conc. before) and after (Conc. after) the sieves:

$$\text{TE \%} = [(\text{Conc. before} - \text{Conc. after}) / \text{Conc. before}] \times 100 \quad (1)$$

The back-wash from this unit was pumped, by a continuously running diaphragm pump, up to a height of 3–4 m, to the top of a thickening sedimentation tank. The settling tank was of a conventional cylindrical design with a conical bottom for sludge collection. The surface water area of the tank was 3.3 m^2 and the volume was 5.5 m^3. The tank was over-dimensioned for the low flow of sludge expected from the dewatering screen, so that the residence time in the tank was more than 9 h. The overflow rate was 0.02–0.2 $m^3 \cdot m^{-2} \cdot h^{-1}$, which was more than adequate to treat wastes with an expected mean settling rate faster than 1 $m \cdot h^{-1}$.

Sludge, tapped from the bottom of the sedimentation tank, was manually transferred to a 500-L stabilisation tank, into which lime was mixed. After stabilisation, the sludge was transferred to a 8-m^3 storage tank. Once or twice each month, the contents of the storage tank were collected by local farmers. The sludge was mixed with manure and then spread on agricultural land.

All water and sludge samples were analysed at Rogaland Research's accredited environmental laboratory. This included suspended dry matter (SDM), total nitrogen (TN), total phosphorus (TP) and total organic carbon (TOC).

The following sludge parameters were analysed: total dry matter (TDM), volatile dry matter (VDM), Kjeldahl nitrogen (TKN), total phosphorus (TP), potassium (K), calcium (Ca), magnesium (Mg), copper (Cu), zinc (Zn), mercury (Hg), lead (Pb), cadmium (Cd), nickel (Ni), chrome (Cr) and cobalt (Co). The TDM, VDM, TKN, TP, K, Ca and Mg, analyses were conducted according to Norwegian standards. Trace metals were determined using an ICP-MS, after digestion with HNO_3^- in a microwave oven.

3. RESULTS

3.1. Experimental tests

3.1.1. Thickening

During March, the settled sludge was removed from the sedimentation tank on a daily basis. As a result of this procedure, the tank functioned adequately, as indi-

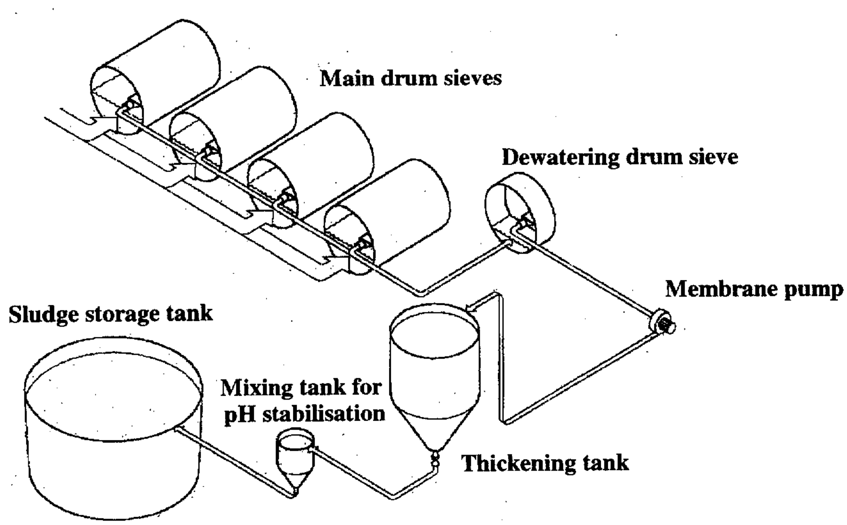


Figure 1. Sketch of the combined effluent treatment and sludge processing system established by Sterner Aquatech Ltd, used as the 'commercial system' at Stolt Sea Farm's hatchery in Fjon, Norway.

cated by a solids removal efficiency generally of 75–90 % (Series 1–12, *figure 2*). Samples taken after March were from a period when the tank was infrequently emptied. This caused fluctuating, and occasionally low, settling efficiency values, as indicated by the quantity of solids collected and the removal efficiency during May (Series 13–18, *figure 2*) and December (Series 19–21, *figure 2*).

Despite the influence of infrequent sludge removal, the treatment efficiency was found to be significantly dependent on the inlet concentration and solids flux (*figure 3*) ($P < 0.05$, df = 20, $r^2 = 0.53$). When adequately operated, i.e. with regular sludge removal, an inlet concentration of about 300 mg $SDM \cdot L^{-1}$ appeared necessary to obtain a solids removal settling efficiency greater than 90 %.

Conversely, treatment efficiency was not found to be significantly influenced by the hydraulic loading ($P = 0.74$, df = 20, $r^2 = 0.006$). The overflow rate was 1.0–2.7 $m^3 \cdot m^{-2} \cdot h^{-1}$, which corresponded to a retention time of 20–60 min. Within these rates, the settling efficiency of the tank was therefore found to be more affected by inlet concentration and flux than by the hydraulic loading.

Based on a settling curve analysis [11], it was found that 75 % of all particles in the back-wash water settled to a 100-cm depth after 60 minutes.

3.1.2. Sludge stabilisation

Ten g CaO and 12.2 g $Ca(OH)_2 \cdot L^{-1}$ sludge were required to obtain a pH of 12 (*figure 4*). This was in accordance with stoichiometric calculations, which predicted that more $Ca(OH)_2$ than CaO is needed to reach a specific high pH value. The amounts added were equivalent to 90 g CaO and 110 g $Ca(OH)_2 \cdot kg^{-1}$ sludge dry matter. Compared to the lime doses used in other stabilisation studies of aquacultural sludge [8], and dewatered sewage sludge [10], the current doses were low. To maintain the pH at levels higher than 12 during long-term storage, the doses needed to be increased so that the initial pH was in the range 12.2–12.3. According to the manufacturer, the maximum obtainable pH value, at the lime qualities used in this study, is pH 12.4–12.5.

The quantity of lime added will increase the volume of sludge produced. Dewatering tests revealed that it was possible to increase the dry matter content of untreated and lime treated sludge by sedimentation from less than 0.05 % up to about 20 % dry matter content within 2 days.

The results of the hygienisation studies are presented in *table I*. *A. salmonicida* was sensitive to high pH values. By raising the pH to 12 by adding $Ca(OH)_2$, the viable count was reduced from 3 10^6 per mL to below the detection limit of 1 10^3 $CFU \cdot mL^{-1}$ within 1 h (> 99.97 % inactivation). At an initial pH of 11.0, the limit of detection was reached after 3 days of incubation. There were no signs of re-growth in either of these batches within a 10-day period. The CFU of untreated sludge sample controls decreased during the incubation period, probably due to the low pH value (5.5) of the raw sludge (from 3 10^6 to 4.5 10^3 over 3 days).

The IPN-virus strain tested was substantially more resistant than *A. salmonicida* to high pH values. At an initial value of pH 11.9, only a slow decline in virus titre was experienced. After 7 days however, the titre decreased to $10^{5.1}$, representing 3.2 log units of reduction (99.94 %). The virus titre in untreated sludge sample controls remained almost stable and close to 10^8 $TCID_{50} \cdot mL^{-1}$ throughout the test period. Among fish pathogenic bacteria and viruses, the IPN-virus is one of the most resistant to various physical and chemical disinfectants [7, 9], and has been used as an indicator in disinfection studies.

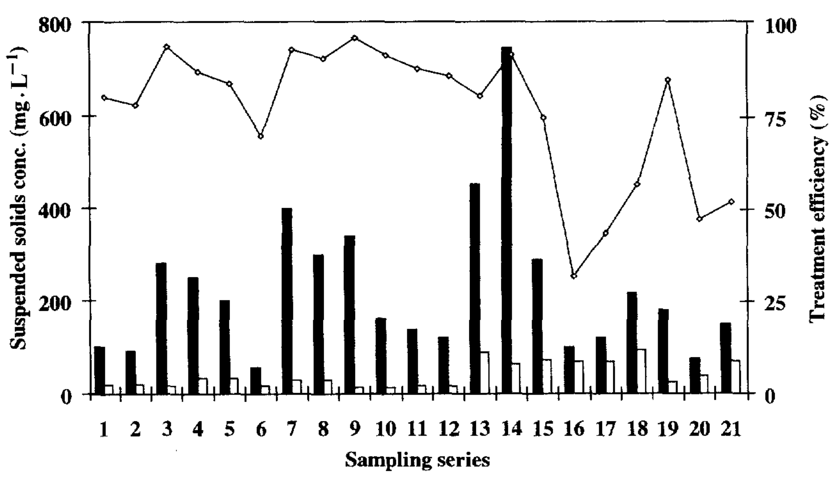


Figure 2. Solids settling results from the back-wash water thickening sedimentation tank in the 'experimental tests' system at Bøvågen Fiskeoppdrett in March '95 (series 1-12), series 13–18 during May '95 (series 13-18) and Dec. '95 (series 19-21). Filled bars: inlet concentration (mg $SS \cdot L^{-1}$). Open bars: outlet concentration (mg $SS \cdot L^{-1}$). Treatment efficiency (%) was defined in equation 1.

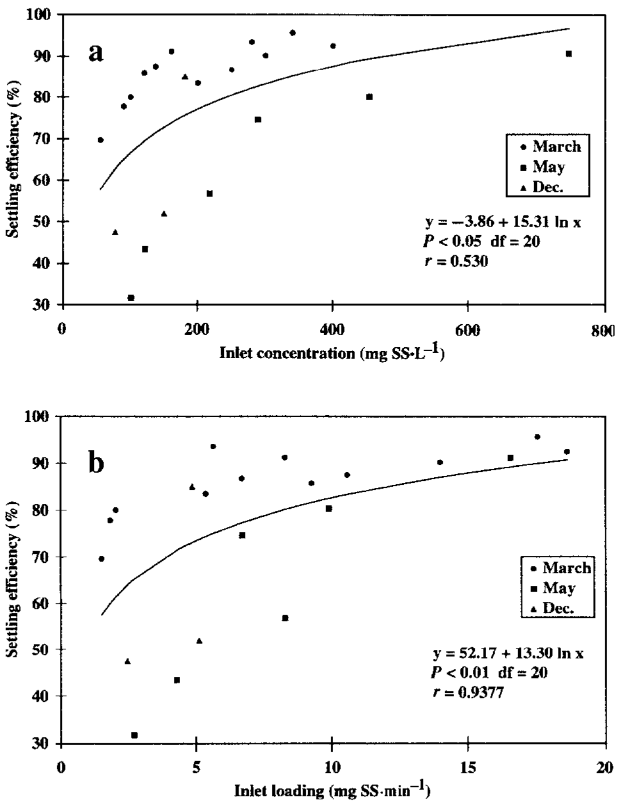


Figure 3. Solids settling efficiency of the sedimentation tank in the 'experimental tests' system at Bøvågen Fiskeoppdrett as a function of: a, inlet solids concentration; and b, inlet mass flow loadings.

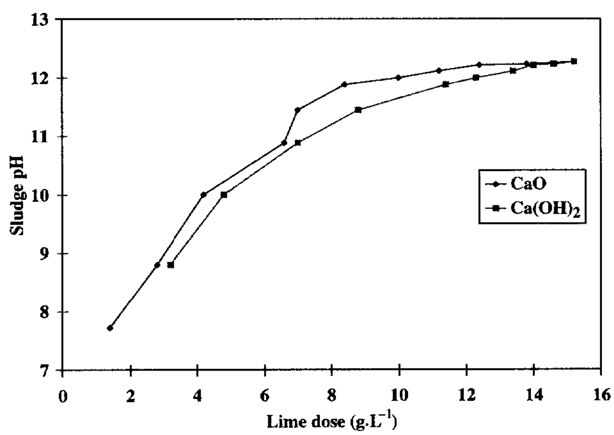


Figure 4. The effect of l lime dosing of aquaculture sludge on sludge pH. Two types of lime (CaO and $Ca(OH)_2$) were added to the sludge, which had a dry matter content of 11.1 %.

3.2. Commercial-scale system

3.2.1. System efficiency

Tests indicated that the removal efficiency of the drum sieves at the study hatchery was 70–75 % for SS and 45–60 % for TP (*figure 5*). Only about 5 % of the TN was removed. The average concentrations of the treated main effluent entering the seawater recipient were (based on several samplings): 0.5–1.2 mg $SS{\cdot}L^{-1}$, 0.03–0.04 mg $TP{\cdot}L^{-1}$ and 0.6–0.8 mg $TN{\cdot}L^{-1}$.

The intermittently flushing system of the main drum sieves produced a back-wash water containing about 1 g $SS{\cdot}L^{-1}$, which was by a factor of 500–1 000 greater than the SS concentration of the main effluent from the fish tanks before treatment. In the dewatering drum sieve, the SS concentration of the back-wash water was further increased by about a factor of 4, to 3–5 g $SS{\cdot}L^{-1}$. The treatment efficiency of this dewatering sieve was 90–99 %. This produced a residual SS concentration in the treated outlet of 17–97 mg $SS{\cdot}L^{-1}$.

Based on a brief sampling of the inlet and outlet water, it was found that about 90 % of the particles settled in the thickening tank. As a result of the combination of a low hydraulic loading (overflow rate of ca. 0.1 $m^3{\cdot}m^{-2}{\cdot}h^{-1}$ at a retention time longer than 24 h) and high inlet solids concentration (ca. 4 g $SS{\cdot}L^{-1}$), the expected settling efficiency was close to 100 %.

The average quantity of sludge produced from daily tapping from the thickening tank was equivalent to 0.7 L $sludge{\cdot}kg^{-1}$ feed supplied. At a dry matter content of 8–12 %, the sludge production was equivalent to 70 g $DM{\cdot}kg^{-1}$ feed. The overall suspended solids removal efficiency of the combined effluent treatment and sludge processing system was then about 50 % for suspended solids (SS), assuming a total solid waste production of about 150 g $SS{\cdot}kg^{-1}$ feed supplied at a feed conversion ratio of 1.0–1.1 kg $feed{\cdot}kg^{-1}$ weight gain. In terms of settleable solids, the assumed overall removal was about 90 % (*table II*). The daily sludge production at the study hatchery was 80–400 L throughout the year.

3.2.2. Sludge quality

Sludge analysis from both fish-farms are presented in *table III*. Except for zinc and cadmium, the concentrations of trace metals appear to be well below regulatory limits for application to land. The zinc concentrations were higher than and the cadmium concentrations close to the upper limit for unrestricted use in agriculture (Norwegian upper limits: 300 mg $Zn{\cdot}kg^{-1}$ and 0.5-0.8 mg $Cd{\cdot}mg\ kg^{-1}$). Westerman et al. [14] reported similar concentration ranges of nutrients and some heavy metals in sludge from trout farms.

During the summer of 1997, the produced hatchery sludge was tested as a fertiliser at a local farm. The results of this trial will be reported at a later date.

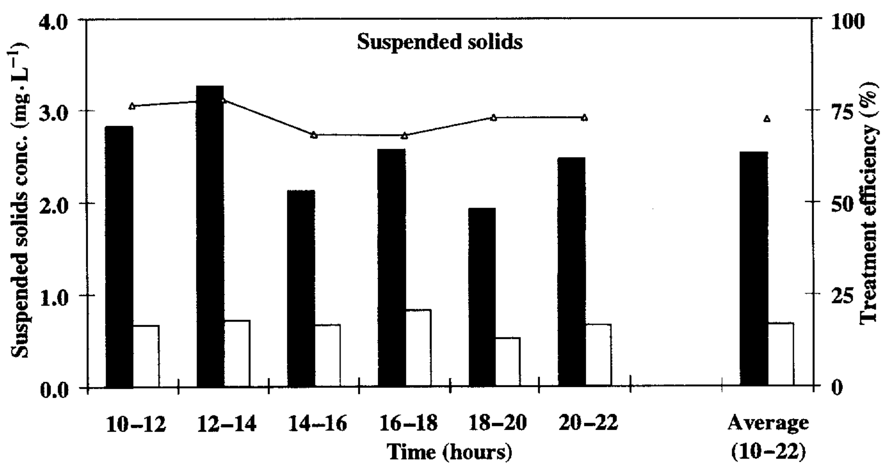
3.2.3. Economy

A brief cost budget of the effluent treatment and sludge processing system at the hatchery was estimated. The fixed costs amounted to about 85 % of the total cost. This was partly due to high invest-

Table I. Inactivation of *Aeromonas salmonicida* and IPN-virus in lime treated sludge at different pH values. The incubation temperature of sludge, from the 'experimental system' at Bøvågen Fiskoppdrett, Norway, containing *A. salmonicida* and IPN-virus was 20 and 15 °C, respectively.

Time	*Aeromonas salmonicida*				IPN-virus	
	pH	CFU·mL^{-1}	pH	CFU·mL^{-}	pH	TCID$_{50}$·mL^{-1}
0	11.0	3.0 10^{6}	12.0	3.0 10^{6}	11.9	10$^{8.3}$
1 h	11.0	2.1 10^{3}	12.2	< 1 10^{3}	11.9	10$^{7.6}$
1 day	-	-	-	-	11.6	10$^{6.1}$
3 days	10.5	< 1 10^{3}	11.4	< 1 10^{3}	-	-
7 days	-	-	-	-	11.4	10$^{5.1}$
10 days	10.6	< 1 10^{3}	11.4	< 1 10^{3}	-	-

ment costs of buildings and fittings, and the considerable over-capacity of the drum sieves, in order to meet future farm expansion. The costs of effluent and sludge treatment, excluding haulage and land-application costs (which were not borne by the fish-farm), amounted to US$ 0.056 per smolt produced, or about 5 % of the total production costs.



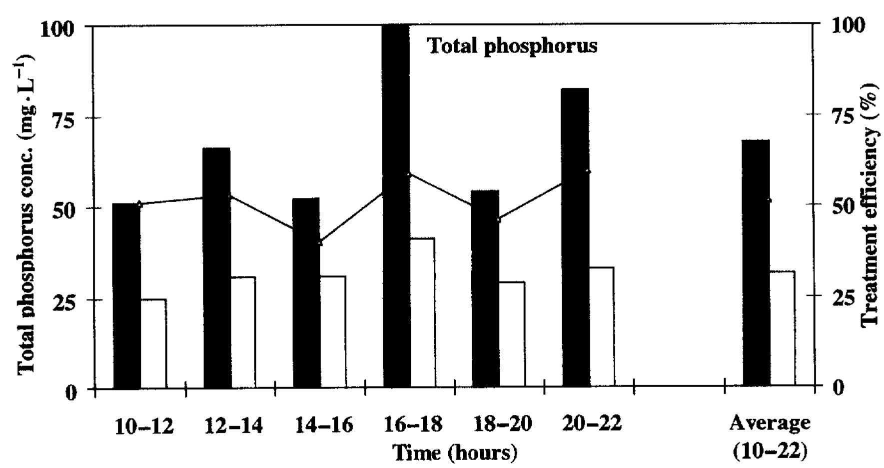


Figure 5. Wastewater concentrations before (filled bars) and after (open bars) the Hydrotech drum screens, with mesh size of 90 µm, used at the 'commercial system' at Stolt Sea Farm's hatchery in Fjon, Norway. Corresponding treatment efficiency is shown by the triangular points.

Table II. A typical mass budget during different seasons at the 'commercial system' at Stolt Sea Farm's hatchery in Fjon, Norway. Assumptions: treatment efficiencies 90, 25 and 50 % for settleable solids, total nitrogen and total phosphorus, respectively. Dry matter content 4 % in settleable solids and 10 % in produced sludge.

Criteria	Spring to autumn	Winter
Farm		
Fish stock (tonnes)	11–45	40
Feed supply ($kg \cdot day^{-1}$)	280–700	125–230
Recipient loading		
Settleable solids ($L \cdot day^{-1}$)		
- before treatment	500–1 000	200–400
- after treatment	50–100	20–40
Total nitrogen ($kg \cdot day^{-1}$)		
- before treatment	10–24	4–8
- after treatment	8–18	3–6
Total phosphorus ($kg \cdot day^{-1}$)		
- before treatment	2–6	1–2
- after treatment	1–3	0.5–1
Sludge production		
Volume ($L \cdot day^{-1}$)	200–400	80–160

Table III. Physical/chemical analyses of settled sludge from the 'commercial system' at Stolt Sea Farm's hatchery in Fjon, Norway. Sampled October 1996–January 1997.

Parameter	Sludge content	Units
Total dry matter (TDM)	14.2–18.6	% of wet weight
Volatile dry matter (VDM)	19.8–29.7	% of dry weight
Total Kjeldahl nitrogen (TKN)	8.1	% of dry weight
Total phosphorus (TP)	4.3	% of dry weight
Potassium (K)	0.04	% of dry weight
Calcium (Ca)	11.3	% of dry weight
Magnesium (Mg)	0.16	% of dry weight
Trace metals:		
Copper (Cu)	24–29	$mg \cdot kg^{-1}$ DM
Zinc (Zn)	562–608	$mg \cdot kg^{-1}$ DM
Lead (Pb)	1.7–2.5	$mg \cdot kg^{-1}$ DM
Cadmium (Cd)	0.60–0.82	$mg \cdot kg^{-1}$ DM
Chrome (Cr)	1.0–2.1	$mg \cdot kg^{-1}$ DM
Nickel (Ni)	10.1–18.6	$mg \cdot kg^{-1}$ DM
Cobalt (Co)	2.4–3.2	$mg \cdot kg^{-1}$ DM

4. DISCUSSION

4.1. Experimental tests

4.1.1. Thickening

The operation and management of a sedimentation tank will greatly affect its settling efficiency (*figure 2*). A poor treatment efficiency was obtained when the tank was infrequently emptied. The most likely reason for this was that fine, slowly settling particles not regularly removed would resuspend. In addition, as the level of sludge builds up, the upper surface comes into contact with increasingly turbulent water, which further increases resuspension. This would lead to reduced treatment efficiencies where the resuspended particles are carried out of the primary outflow. Intermittent increases in the hydraulic load on the settling tank would further increase resuspension and hence cause the fluctuating settling efficiencies that were evident.

The settling efficiency of the tank was found to be significantly influenced by inlet concentration and not hydraulic loading. The likely explanation for this is that the tank was somewhat over-dimensioned and so received flow rates that were well below its maximum overflow rate capacity. Variations in in-flow rates were within limits that could be treated by the tank. A high inlet concentration on the other hand produced a high treatment efficiency, possibly because concentrations were high enough to cause faster flocculent settling [11]. It is also possible that the effluents with larger particles, that sink faster, gave rise to higher loads. In order to maintain high treatment efficiencies, it is therefore clear that dilute back-wash water from the screen or first particle separation stage should be avoided. This confirms conclusions presented by Cripps and Kelly [4] which recommended that sedimentation tanks should only be used for secondary thickening and not for separating the dilute wastes in the primary effluent from aquaculture facilities.

Settling curve analysis results indicated a sedimentation rate of approximately 0.6 $m \cdot min^{-1}$, which was within the range of 0.2–1.8 $m \cdot min^{-1}$ suggested by Warrer-Hansen [13]. Results from this study should then be applicable for a range of fish-farm operations in which dilute sludge (but nevertheless at a higher waste concentration than the primary effluent) is to be treated.

4.1.2. Sludge stabilisation

Available literature on lime stabilisation and hygienisation of sludge does not include inactivation experiments on fish pathogenic micro-organisms. The effectiveness of raising the pH by the addition of sodium hydroxide, in order to inactivate fish pathogens (including *Yersinia ruckeri* and IPN-virus) in wastewater from slaughterhouses, has been evaluated [7]. Elevation of pH to ≥ 12, with a contact time of 24 h, was shown to destroy the pathogen tested, and is one of the methods approved by the Norwegian veterinary authorities for the disinfection of effluents from the fish processing industry. There are indications that the agent of infectious salmon anaemia (ISA) will also be destroyed at such sodium hydroxide dose [12].

Some scientific work has been published on lime hygienisation of sewage sludge [5, 6]. Current guidelines [6] to eliminate the most resistant human pathogens recommend CaO or $Ca(OH)_2$ addition to pH values above 12, followed by long-term storage, of up to 3 months, prior to application on agricultural land. If sufficient lime, as CaO, is added to dewatered sludge with a high solids content, an additional hygienisation effect can be obtained from the temperature increase developed by the exothermic hydrolysis of CaO.

In conclusion, lime treatment and storage is a promising technique for the stabilisation and hygienisation of aquacultural sludge prior to application on agricultural land. In the present study, counts of *A. salmonicida* and IPN-virus were reduced by more than 99.9 % in lime treated sludge at pH 12 within 7 days.

4.2. Commercial-scale system

4.2.1. System efficiency

The removal efficiency of SS and TP achieved was within the range expected when using sieves with a mesh size of 80–100 µm [4]. The dissolved fractions of the TP and TN are mainly unavailable to particle separation techniques, and hence overall treatment efficiencies result from the reduction in only part of the total waste flow, i.e. the suspended fraction. This is a major limitation of particle removal systems, but such systems are currently the most suitable currently commercially available for flow-through aquaculture facilities, with respect to capacity, costs, operation and facilities required [3].

The treatment efficiency, at the sieve dewatering stage, of 90–99 % can be considered high. A lower removal efficiency of 80 % was found in a similar system, using a rotating screen (mesh size 30 µm) for dewatering back-wash water [1].

A high treatment efficiency was expected at the sedimentation tank stage, due to the low hydraulic loading, which would have allowed sufficient time for even the majority of slow sinking particles to settle. At a similar hydraulic loading however, Bergheim et al. [1] found a treatment efficiency as high as 95–99 %, which was substantially higher than that obtained in the present study. The low treatment efficiency at the sampling time was probably due to infrequent sludge removal, as discussed previously.

The running overall efficiency of the combined effluent treatment and sludge processing system was however fairly high, at about 50 % for SS. Based on the content of TP and TN in the produced sludge, the nutrient removal rate was clearly higher than short-term sampling results would indicate.

4.2.2. Sludge quality

Utilised as an organic fertiliser in agriculture, fish-farm sludge can be a good source of nitrogen and phosphorus as a slow release fertiliser [14], but the content of potassium is negligible. The lime content of stabilised sludge (12–18 % of DM) can improve the alkalinity of acid soils. Except for zinc and cadmium, the concentrations of trace metals appear to be well below regulatory limits for application to land. The zinc concentrations were higher and the cadmium concentrations close to the upper limit for unrestricted use in agriculture. In order to reduce concentrations of these trace metals to below regulatory limits, the fish-farm sludge was diluted with liquid manure from cattle. Westerman et al. [14] reported similar concentration ranges of nutrients and some heavy metals in sludge from trout farms.

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