An integrated wastewater treatment system for land-based fish-farming

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Received 3 January 1999; accepted 1 January 2000

Abstract

A newly developed low cost system for fish-farm wastewater treatment was evaluated. The system consisted two major parts: (1) a new type of square tank design with two separate outlets, i.e. one centrally positioned high solids concentration outlet and one corner located low solids concentration primary outlet; and (2) a stationary bowed screen for solid removal from the high solids effluent. Removal rates for the particle outlet were on average 43.2% total phosphorus (TP) and 7.3% TN. The mean TP, TN, chemical oxygen demand (COD) and TS removal rates of the bowed screen were 49.3, 42.7, 48.0, and 74.4%, respectively. TP and TN waste removal rates for the whole system were 21.3 and 3.1%, respectively. The self-cleaning in the tank was poor at the start of the trials, but improved throughout the experimental period as fish density increased, thus also increasing the removal rates for the whole system. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Wastewater treatment; Dual-drain tank; Bowed screen

1. Introduction

Different systems for fish-farm wastewater treatment have been reported, but these all have high capital costs (Bergheim and Cripps, 1998). The acceptable additional investment costs for effluent treatment increases with increased fish production (Muir, 1982). Only low cost systems for wastewater treatment are therefore economically viable in small-scale farms. A vital part of the concept

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PH: S0144-8609(00)00039-X
presented, is the introduction of a new type of dual-drain tanks. This is an approach which has large economic implications (Timmons and Summerfeldt, 1997). Particle traps in dual-drain tanks have been shown, in several tests, to be highly efficient (Summerfeldt and Timmons, 1998). Commonly both high and low solids outlet are positioned in the centre of normal dual-drain tanks. The high solids concentration outlet was positioned in the centre and the low solids concentration primary outlet was located in the corner of the tank in this study. The primary outlet was build as an integral part of the tank construction. By locating the primary outlet in the corner, the cost of the outlet system was reduced because the length of the main outlet pipe out from the tank was shortened. The water flow through the tank could also be increased without the problematic swirl in the centre of the tank, which can be a problem in traditionally designed tanks with centre drains. Tank self-cleaning was an important design evaluation criteria.

As a secondary treatment unit, a bow-shaped static microscreen, was used for solid separation from the high solids effluent from the tanks. This microscreen has recently been applied for aquaculture operations. Thus, the wastewater treatment system studied was based on in-tank solid separation, followed by solids separation by screening.

2. Material and methods

2.1. Experimental conditions

The experiment was conducted at the commercial fish-farm, Fjordroye, during the period 10 July to 8 August 1997. A total of 8203 charr (2+), bred from a local stock, were transferred to the tank on 3 June. The fish were subject to 14 h of light per day, between 08:00 and 22:00 h, regulated by a timer without dimming.

The feed used was 2.5 mm ‘Vivaldi’ pellets from Skretting with the following composition: protein, 45.2%; fat, 26.5%, DM, 90.3%; Ash, 10%; total phosphorus (TP), 15 g/kg; TN, 72 g/kg; chemical oxygen demand (COD), 1665 g/kg; digestible energy, 21.5 MJ/kg. The fish were fed throughout the light period in batches of 30–35 g every 3–4 min from an automatic feeder. In addition, the fish were appetite fed by hand once or twice per day at varying times. The water temperature was measured daily.

2.2. Tank design

The production volume of the newly designed concrete tank used was 55 m³, and the water height 2.6 m. The side walls had an inner length of about 4.8 m (Fig. 1). The corners of the square tank were rounded using aluminium plates to improve the hydrodynamic characteristics. The choice of a square shape was a concession to reduced tank construction costs.

The settled particles should, if the system functioned well, be transported out through a central high solids concentration outlet. This comprised a grating and
funnel (diameter 15 cm) at the bottom of the tank, from which the high solids concentration outlet water was led through a pipe (diameter 1.1 cm) to a stationary bowed screen separator.

The tank water flow, throughout the experimental period, was about 1100 l/min. The water velocity in the tank was measured on the 12 July using a digital anemometer. On average, the current velocity was kept stable at approximately 6 cm/s (average of 36 measuring points in the tank).

2.3. The stationary screen

In the experiment, a stationary bowed screen (Reko 600 LB) made of stainless steel, with a screen pore size of 250 μm was tested. The screen membrane was constructed of horizontal triangular guide rails, welded in parallel and spaced 250 μm apart. This construction was aimed to ensure a high hydraulic capacity and good self-cleaning. Manufacturer recommended flow across the screen was 120–430 l/min. The unit tested in this experiment had a capacity sufficient for a 50 tonnes farm. The screen was placed at the same height as the bottom of the fish tank. Only the high solids concentration outlet was led to the screen, hence flow rates were only 4–5 l/min. Only a small part of the area of the screen was therefore used. The effective part of the screen used was approximately 4–6 cm in length. The screen was flushed daily with water and scrubbed manually with a brush for 5 min, to avoid clogging of the screen.

2.4. Sampling and analysis

A random sample of fish were anaesthetised and weighted at the start and end of the experiment (Lekang and Dalen, 1994). In addition, the lengths and weights of 100 individual fish were measured. Number of dead fish, weight of dead fish,
amount of feed assign per day (approximate) and the total use of feed during the experimental period, were noted.

All the solids separated by the bowed screen during the experimental period were collected in a bucket that was emptied into a storage barrel once a day. Ant-acid with antioxidant (500 ppm etoxiquin) was added in the barrel, to avoid oxidation and decomposition of the organic matter. The pH was maintained continuously below 4.0. At the end of the experimental period, the total volume of sludge collected was measured. The sludge was then homogenised by vigorous shaking prior to the removal of samples for analysis of: TP; total Kjeldahl nitrogen (TKN); COD; total solids (TDM); ash weight and pH. It should be noted that TKN does not include nitrate/nitrite-N. These N-fractions can however be neglected in flow-through fish farms so TKN "TN. These sludge parameters were analysed in accordance with Norwegian Standard Methods.

A single sludge sample was taken on the last experimental day to indicate the expected sludge quality over a longer time.

Water was sampled on 23 July, 26 July and 7 August from four places: tank inlet; primary outlet; sludge outlet before the bowed screen and after the bowed screen. Each sample consisted of 1.5 l integrated from 24 individual samples taken once an hour over a whole day.

The water samples were stored in polyethylene bottles at -20°C, prior to analysis of: TP, TN, COD and TDM (analytical methods: Norwegian Standard). Fish farm-effluent solids are usually determined as total suspended solids (TSS) based on immediate filtration after sampling. In the absence of filtration equipment at the sampling site, TDM analysis was conducted instead.

2.5. Calculations

Based on water sample analysis results from different points within the system (Fig. 2) (i.e. short-term rates) the removal efficiency of the dual drain tank (1.), the bow screen (2.) and whole system (3.) were calculated where: 1 = flux in the inlet water (g/day); a = flux in the centrally positioned high solid outlet (g/day); b = flux in the high solid primary outlet (g/day); c = flux in the outlet water from the bow screen (g/day).

1. Partition coefficient between drains (%) = \( \frac{a}{a + b - i} \times 100 \)

This indicates the efficiency of operation of the dual drain system, and was determined for TP and TN.

2. Screen efficiency (%) = \( \frac{a - c}{a} \times 100 \)

Indicates the efficiency with which the screen system to removes solids from the high solid drain, and was determined for TP, TN, COD and TDM.
Fig. 2. Sketch of the system in which the removal efficiency was determined.

3. System efficiency (%), determined for TP and TN

\[ \text{System efficiency (long term)} = \frac{a - c}{a + b - i} \times 100 \]

Indicates the efficiency of operation of the whole system, and was determined for TP and TN.

The removal rates for the system were also calculated based on total assigned feed (kg), increase in fish biomass (kg), and collected waste (kg) (i.e. long-term rates). The removal efficiency of the whole system (3) and the bow screen (2) was calculated as:

3. System efficiency (%), determined for TP and TN

\[ \frac{\text{Removed in sludge (kg)}}{\text{Supplied in feed} - \text{Retained in fish(kg)}} \times 100 \]

2. Screen efficiency (%), determined for TP and TN

\[ \frac{\text{System efficiency (long term} - 3)}{\text{Dual drain efficiency (short time} - 2)} \times 100 \]

Few data have been published quantifying the phosphorous content of Arctic charr (Salvelinus alpinus). Based on reported contents found in other salmonids (Shearer et al., 1994), the assumed content of the studied charr was 4.5 g TP/kg whole body. Approximately 17% of the whole body is protein (Jobling, 1983) which corresponds to a content of about 27 g TN/kg body weight of charr.
3. Results and discussion

3.1. Growth and mortality

The fish density increased from 12 to 21 kg/m³ during the experimental period. Average daily growth rate over the study period was 1.85% at an average temperature of 13.2°C (7–15°C), while the estimated model-based growth rate was 1.45% (Jobling et al., 1993). The individual weight distribution declined slightly, and the average condition factor (CF) increased from 1.26 to 1.39 (Table 1). The total biomass gain (including dead fish) was 464 kg at a total feed consumption of 369 kg. Consequently, the biological feed conversion ratio (FCR) was 0.80 kg feed/kg fish weight gain (Table 3). There was a low mortality during the experimental period with eight dead fish out of a total of 8600 fish (< 0.1%).

3.2. Tank self-cleaning

Initially, the tank was not self-cleaning. Some faecal waste and feed loss accumulated in a small area of the tank bottom during the first 2 weeks. Settled solids were removed by a siphon on the 26 July. During the rest of the experimental period and throughout the autumn, no settled solids were observed in the tank.

The flow velocity measured at 36 points within the tank was in the range 1.0–12.6 cm/s, (mean about 6 cm/s). The flow velocity along the tank bottom (on average 3.0–9.1 cm/s) was lower than that recommended to achieve efficient self-cleaning (Tvinnereim, 1994). A possible explanation of the gradually improved self-cleaning was the increased fish density throughout the test period. Earlier experiments with a dual-drain circular tank (‘Cornell-type’), with separate drains, also demonstrated low cleaning efficiency without fish, but a good efficiency with fish stocked (Timmons et al., 1999). This indicates that the movement of the fish probably more effectively transports the solids along the tank bottom to the centre than the primary flow alone.

3.3. In-tank separation

Only 0.3–0.4% of the total flow was led through the high solids concentration outlet. The concentrations of TP and TN were on average 270 and 18 times higher, respectively, than concentrations in the primary outlet (Table 2). Due to low TS

Table 1

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Weight (g)</th>
<th>Length (cm)</th>
<th>CF</th>
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</thead>
<tbody>
<tr>
<td>Start (10.07.97)</td>
<td>90</td>
<td>82.6 ± 36.7</td>
<td>18.3 ± 2.5</td>
<td>1.26 ± 0.1</td>
</tr>
<tr>
<td>End (08.08.97)</td>
<td>114</td>
<td>139.9 ± 59.7</td>
<td>21.1 ± 2.9</td>
<td>1.39 ± 0.1</td>
</tr>
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Table 2
Concentrations, fluxes and removal rates of the wastewater treatment system

<table>
<thead>
<tr>
<th>Sampling date</th>
<th>Parameter</th>
<th>Inlet</th>
<th>Main outlet</th>
<th>High solids outlet</th>
<th>Removal rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Before screen</td>
<td>After screen</td>
</tr>
<tr>
<td>23 July</td>
<td>Water flow (l/min)</td>
<td>1123</td>
<td>1119</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>26 July</td>
<td>TP (µg/l)</td>
<td>1020</td>
<td>1016</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>7 Aug</td>
<td>TP (µg/l)</td>
<td>1123</td>
<td>1119</td>
<td>3.7</td>
<td>3.7</td>
</tr>
<tr>
<td>23 July</td>
<td>TP flux (g/day)</td>
<td>1</td>
<td>52</td>
<td>3300</td>
<td>2800</td>
</tr>
<tr>
<td>26 July</td>
<td>TP flux (g/day)</td>
<td>1.6</td>
<td>83.8</td>
<td>20.5</td>
<td>17.4</td>
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<tr>
<td>7 Aug</td>
<td>TP (µg/l)</td>
<td>1</td>
<td>26</td>
<td>14000</td>
<td>3500</td>
</tr>
<tr>
<td>23 July</td>
<td>TN (mg/l)</td>
<td>0.08</td>
<td>0.35</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>26 July</td>
<td>TN (mg/l)</td>
<td>0.06</td>
<td>0.36</td>
<td>5.0</td>
<td>2.2</td>
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<tr>
<td>7 Aug</td>
<td>TN (mg/l)</td>
<td>0.05</td>
<td>0.25</td>
<td>8.6</td>
<td>2.4</td>
</tr>
<tr>
<td>23 July</td>
<td>COD (mg/l)</td>
<td>&lt;3</td>
<td>&lt;3</td>
<td>41</td>
<td>41</td>
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<tr>
<td>26 July</td>
<td>COD (mg/l)</td>
<td>&lt;3</td>
<td>&lt;3</td>
<td>75</td>
<td>28</td>
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Table 2 (Continued)

<table>
<thead>
<tr>
<th>Sampling date</th>
<th>Parameter</th>
<th>Inlet</th>
<th>Main outlet</th>
<th>High solids outlet</th>
<th>Removal rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Before screen</td>
<td>After screen</td>
</tr>
<tr>
<td>7 Aug</td>
<td>COD (mg/l)</td>
<td>&lt;3</td>
<td>&lt;3</td>
<td>160</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>COD flux (g/day)</td>
<td>–</td>
<td>–</td>
<td>843</td>
<td>158</td>
</tr>
<tr>
<td>23 July</td>
<td>TS (mg/l)</td>
<td>&lt;10</td>
<td>&lt;10</td>
<td>80</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>TS flux (g/day)</td>
<td>–</td>
<td>–</td>
<td>497</td>
<td>186</td>
</tr>
<tr>
<td>26 July</td>
<td>TS (mg/l)</td>
<td>&lt;10</td>
<td>&lt;10</td>
<td>190</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>TS flux (g/day)</td>
<td>–</td>
<td>–</td>
<td>1084</td>
<td>171</td>
</tr>
<tr>
<td>7 Aug</td>
<td>TS (mg/l)</td>
<td>&lt;10</td>
<td>&lt;10</td>
<td>170</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>TS flux (g/day)</td>
<td>–</td>
<td>–</td>
<td>896</td>
<td>211</td>
</tr>
</tbody>
</table>

*₁₁, ₂₁, ₃₁: see Section 2.
and COD concentrations in the inlet and primary outlet (lower than analytical detection levels), no separation efficiency estimations were possible to calculate. The average in-tank removal rates of TP and TN were 43.2 and 7.3%, respectively. Throughout the test period, the efficiency of the dual-drain system increased significantly. At the last sampling (7 August) potential efficiency of the system was demonstrated.

Dual-drain fish tank systems have been reported for more than 50 years (Cripps and Poxton, 1992; Summerfeldt and Timmons, 1998). In reported tests of such systems the high solid outlet flow represented 6–10% of the total tank flow (Mäkinen et al., 1988; Ulgenes and Eikebrokk, 1994); or about 20–30 times the high solids outlet flow in the present study. The high solid outlet flow was probably too low to obtain maximum removal of solids, especially during the first part of the study.

The high solid outlet concentrations were in the same range as reported for microscreen backwash water with continuous screen flushing (backwash flow 2–3% of total flow), but lower than backwash water concentrations with intermittent flushing (Bergheim et al., 1993, 1998; Ulgenes and Eikebrokk, 1994). Pre-concentrated effluent from dual-drain tanks and backwash water from micro-screens typically contain less than 1 g suspended solids (SS)/l and must be further thickened.

3.4. Screen separation

In the first test (Table 2), the removal efficiency of the screen was low (TP) or negligible (TN, COD). This efficiency though, as with the dual-drain system, greatly increased in following tests, to 56–84% for all measured parameters. The removal rate of solids (TS) was reasonable high in all three tests, at 63–84%.

The efficiency of micro-screens in removing particles from fish tank outlets is closely dependant on the screen mesh size and inlet concentrations (Cripps and Kelly, 1996). Few reports of using screens as secondary dewatering devices have been published (Bergheim et al., 1993). In a running test, backwash water from a band filter was dewatered by a similar screen to that described in the present study (stationary bowed screen, mesh size 200 μm). A solids removal of about 90% was demonstrated (Håkonsund, personal communication).

3.5. Mass budget and system efficiency

The estimated long-term TP and TN removal rates of the tank dual-drain and the screen were 22.5 and 2.7%, respectively (Table 3). These values were within the range of the estimated short-term total removal rates, 3–49% for TP and 0–9% for TN (Table 2). 52.1% of TP and 36.4% of TN was estimated to have been removed across the screen.

Generally, a significantly higher fraction of TP than TN is particle-bound (Cripps, 1995), so mechanical treatment more efficiently removes TP than TN. Reported SS removal rates are about the same or higher than the removal of TP (Cripps and Kelly, 1996).
Table 3
Mass budget based estimates of effluent load, treatment efficiency for the complete wastewater treatment system and for the bowed screen

<table>
<thead>
<tr>
<th>Criteria</th>
<th>TP</th>
<th>TN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supplied in feed (kg)</td>
<td>5.5</td>
<td>26.6</td>
</tr>
<tr>
<td>Retained in fish stock (kg)</td>
<td>2.1</td>
<td>12.5</td>
</tr>
<tr>
<td>Collected sludge (kg)</td>
<td>0.8</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Effluent load:

<table>
<thead>
<tr>
<th></th>
<th>kg</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>% of supplied</td>
<td>47.3</td>
<td>51.5</td>
</tr>
<tr>
<td>g/kg feed</td>
<td>7.2</td>
<td>37.0</td>
</tr>
<tr>
<td>g/kg fish gain</td>
<td>5.8</td>
<td>29.5</td>
</tr>
<tr>
<td>Total removal rate, $3_2$ (%)</td>
<td>22.5</td>
<td>2.7</td>
</tr>
<tr>
<td>Screen removal rate, $2_2$ (%)</td>
<td>52.1</td>
<td>36.4</td>
</tr>
</tbody>
</table>

*a $3_2$, $2_2$: see Section 2.

In a similar system, combining dual-drain fish tanks with screen separation (Triangle Filter, mesh size 60 μm), an average of 46% TP was removed (Mäkinen et al. 1988). An effluent treatment system based on dual-drain tanks (particle trap system) and rotating microscreens (mesh size 60 μm) was tested in a land-based farm for on-growing salmon (Ulgenes and Eikebrokk, 1994) and the following long-term removal efficiencies were reported: 79–80% for SS; 30–47% for TP; and 13–18% for TN.

Based on mass budget calculations, 47.3 and 51.5% of the TP and TN supplied, respectively, were discharged into the recipient in the effluent after treatment (Table 3). The specific TP and TN load levels were 5.8 and 29.5 g/kg fish gain, respectively. Undoubtedly, the feed contained excess phosphorus because the dietary requirements for optimum growth are within the range 0.5–0.8% TP (Lall, 1992). Using salmonid diets where a part of the fish meal is replaced by soya meal, the post-treatment discharge of phosphorus should be reduced to 3–4 g TP/kg gain (Bergheim and Sveier, 1995). In practice, a discharge of 30 g TN/kg gain was difficult to reduce significantly.

At conditions encountered during this experiment (15 g P/kg feed, FCR 0.80) the fish were supplied with 12 g phosphorus/kg weight increase. This weight increase corresponded to an amount in the wastewater of 7.5 g P/kg produced fish (4.5 g P/kg fish).

3.6. Sludge characteristics

The average dry matter content in sludge collected throughout the test period was 5.6% (Table 4). The content of TP was double that of the TKN content, 68 and 32 g/kg TDM, respectively. A COD/TDM ratio of ca. 1.3 was measured.

Reported analysis of newly processed sludge at other salmonid farms indicates a higher TKN content than TP (Bergheim et al. 1998). The reasons for the low
TKN/high TP content in the current study were probably a combination of a high feed utilisation (low FCR) causing a low particle-bound nitrogen fraction (Jobling, 1994), and a feed containing excess phosphorus. The sludge COD found was relatively high compared with Chen et al. (1993) who reported a COD/TDM ratio of about 0.5 in newly produced trout sludge.

In order to produce a stabilised fish-farm sludge, free of pathogenic micro-organisms, about 100 g CaO/kg sludge DM has to be added to the raw sludge to maintain a pH level of at least 12.0 (Bergheim et al., 1998). Sludge pathogens, such as ILA virus and *Aeromonas* bacteria, can be inactivated in a liquid composting reactor (Lekang et al., 1997). The average sludge dry matter content (5.6%) is considered optimal for application to land by conventional vehicles equipped for transport and spreading of liquid manure.

4. Conclusions

- The low cost integrated system for wastewater treatment evaluated in this study was reasonably effective for the treatment of fish-farm wastewater.
- The dual drain tank with a primary outlet in the corner self-cleaned poorly at the start of the experiment, but improved throughout the experimental period as the fish density increased. At the end of the study the self-cleaning seemed satisfactory.
- Reasonably good removal rates, of an average 43.2% for TP and 7.3% for TN, were achieved from the use of the dual drain tank as the first cleaning step. There was a great improvement in the removal rates from the particle outlet throughout the experimental period as the fish density increased.
- Static bowed screen separators appear suitable for the treatment of wastewater from land based fish farms.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Sludge content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A (min–max)</td>
</tr>
<tr>
<td>TDM</td>
<td>% of wet weight</td>
<td>5.6 (5.6–5.7)</td>
</tr>
<tr>
<td>TP</td>
<td>g/kg TDM</td>
<td>68 (67–69)</td>
</tr>
<tr>
<td>TKN</td>
<td>&quot;</td>
<td>32 (31–32)</td>
</tr>
<tr>
<td>Ashes</td>
<td>&quot;</td>
<td>461 (455–464)</td>
</tr>
<tr>
<td>CODb</td>
<td>&quot;</td>
<td>1288 (1093–1388)</td>
</tr>
<tr>
<td>pH</td>
<td>&quot;</td>
<td>3.5 (± 0.0)</td>
</tr>
</tbody>
</table>

*a* A: mixed samples collected daily during the study period (*n* = 3); B: a single sample collected on 8 August.

*b* COD unit: g O₂.

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Table 4

Sludge analysis results*
• No sludge dewatering stage was required prior to hygenisation/stabilisation and storage.

Acknowledgements

This research was funded by the Norwegian Research Council, and the Agricultural Development Fund. We would like to thank Dr S.J. Cripps for advice on the content and language of this manuscript.

References