WASTE LOADINGS FROM TWO FRESHWATER ATLANTIC SALMON JUVENILE FARMS IN SCOTLAND

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Abstract. Studies of waste generation from the freshwater phase of Atlantic salmon (*Salmo salar* L.) production have not been substantially updated since the mid 1980's, and advances in husbandry prectices designed to reduce wastage which have taken place in that period therefore remain unconsidered. In order to determine if reductions have been achieved, two Scottish fish farms were visited on a number of occasions during one year, and outputs of suspended solids (SS), biochemical oxygen demand (BOD), total ammonia nitrogen (TAN) (NH_3+NH_4^+), dissolved reactive and total phosphorus (DRP, TP) were monitored. The range of waste loadings obtained were 9.1-10.0 kg TP t fish^{-1} yr^{-1}, 410 kg BOD_5 t fish^{-1} yr^{-1}, 191-606 kg SS t fish^{-1} y^{-1}, and 20.3-39.3 kg TAN-N t fish^{-1} yr^{-1}. Compared to existing data, a greater range of daily waste loadings were observed, suggesting that more frequent monitoring is required to reduce variations observed in the data set, and to obtain accurate information on waste outputs from such operations. Modifications of feeding methods remains a route through which further reductions in waste outputs may be made.

1. Introduction

The production of Atlantic salmon (*Salmo salar* L.) juveniles (parr) in Scottish freshwaters is for the purposes of supplying marine sites with new fish for ongrowing to marketable size. In 1990, total production of such juveniles amounted to 21.8 million fish (NCC, 1990). Use of floating cages accounts for about half of the freshwater production, the remainder being reared in tank facilities. In 1989 there were 98 tank sites involved in parr production (NCC, 1990). The high water quality requirements for freshwater salmon farming, together with a preference for sites in close proximity to marine ongrowing facilities has led to a concentration of freshwater salmon farms in the West Highlands of Scotland and to a lesser extent, Strathclyde Region (NCC, 1990). This requirement for high quality water represents a possible conflict of resource usage, as many fish farms discharge to freshwaters which have been designated as Class 1 by the Scottish Development Department for the purposes of their national water survey (HRPB, 1987). The consent to Discharge issued for fish farms normally stipulates a maximum production and standing stock based on type, size and location of farm as well as the Environmental Quality Standard of the water body. Consents for fish farm waste waters are

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based typically upon concentrations of suspended solids (SS), biochemical oxygen demand(BOD_5), dissolved oxygen, pH and total phosphorus (TP) and dissolved reactive phosphorus (DRP). However, other parameters, such as concentrations of chemical treatments, may also be included if a given River Purification Authority perceives a need for such additional legislation.

Effluent from aquaculture tends to be relatively dilute compared to those discharged from other industries (Alabaster, 1982; Beveridge *et al.*, 1991). Many studies have been undertaken to quantify waste loadings in fish culture systems, but there remains a dearth of published information on freshwater Atlantic salmon systems (Storrebaken and Austreng, 1987). The majority of work has been concerned with adult stages of *S. salar* (Fivelstad *et al.*, 1990; Bergheim *et al.*, 1991) or rainbow trout (*Oncorhynchus mykiss*) installations (Bergheim *et al.*, 1982, 1984; Beveridge *et al.*, 1991; Butz and Vens-Cappell, 1982, Clark *et al.*, 1985, Foy and Rosell, 1991a, b). Atlantic salmon parr production is, unlike rainbow trout production, concerned not with growth of stock for the food fish market, but growing the fish to the stage at which they are sufficiently mature (termed *smolts*) to be transferred to marine sites for ongrowing to marketable size.

Approximately 74% of commonly available commercial diets are digestible on a dry weight basis (Beveridge, 1987). Therefore, not only is feed wasted, dry pellet loss from salmon and trout culture being estimated as between 5 and 20%, but also around 26% of the diet is voided in fish faeces without digestion (Beveridge *et al.*, 1991). Feed at fish farms is wasted for several reasons such as supply in excess of dietary requirement, unpalatability of diet (Bromage *et al.*, 1990), poor ingestion rates due to feeding practices and other management considerations such as high stocking densities (Kilambi *et al.*, 1977). Feed wastage is obviously an important determinant of effluent water quality. Solids also account for a significant proportion of the BOD in fish farm waste waters (Henderson and Bromage, 1988).

Fish farm discharges are characterised by dissolved and solid components. In terms of dissolved loads, ammonia and urea from the catabolism of protein are important, although nutrients such as phosphorus leached from the solid waste fraction also contribute to the dissolved discharge. Undigested food together with mucus, intestinal cells and bacteria associated with faeces constitute the solid load, while nutrients absorbed to excess are excreted as soluble waste. Owing to different farm practices and systems, waste outputs in aquacultural effluent may vary substantially. Size of fish influences the size of the pelleted feed, and therefore the initial size of waste particles. The type of farming system used affects how much food is lost, duration of availability of solids for leaching within the system and, to a large extent, to what degree solids distintegrate. A greater break up of solids increases the difficulty involved in removal, and also increases the surface area available to allow release of nutrients into solution. The accumulation of organic matter in a river channel can lead to degradation of downstream biological communities; Carr and Goulder (1990a, b) identified such downstream impacts of fish farm discharges on the River Hull, UK. Growing concern over possible environmental impacts of freshwater fish farming in Scotland and increasing restrictions placed on aquacultural installations have resulted in a requirement for more detailed information on discharges from *S. salar* tank and cage farms. Given the differences in both the practices and objectives of freshwater salmon and trout farming, and in order to retain satisfactory control of waste outputs, it is necessary to obtain figures derived specifically from *S. salar* freshwater sites. In addition, data used in predicting impacts of fish farms may now be outdated, since feed manufacture and management practices have changed significantly since the last widely quoted survey of land based fish farm waste outputs (Alabaster, 1982). The aims of this project were therefore to quantify effluent loadings from *S. salar* production in tank culture installations in Scotland.

2. Materials and Methods

2.1. STUDY SITES

Two Atlantic salmon freshwater farms were chosen as representative of the range of production system size most commonly found in Scotland. Sites 1 and 2 were chosen respectively as examples of large and small scale productions units found in Scotland. Site 1 is situated in North West Scotland which abstracts from and discharges to a river. Discharge volume from the site is approximately 700 L s^{-1}. Annual production is in the region of 1.0–1.2 million smolts, and the site was visited on five occasions during 1990 (Table I). Unlike Site 2, Site 1 supplies fish to other sites in Scotland, final biomass is therefore low at the site, although numbers of fish produced are high (Table I). Site 2 is located in Central Region of Scotland, and abstracts and discharges water to the same stream. Average water flow through Site 2 was 84 L s^{-1}. Annual production was approximately 102 000 smolts. Data was collected on six occasions (Table I).

2.2. SAMPLE COLLECTION

Samples were taken hourly at each site over a 24 hr period (commencing at 0700 hr), on a number of accasions during one year, in order to account for the variability in waste loadings as a result of the different lifestages of the fish, and husbandry conditions (*i.e.* stocking density, flow rates etc.). Sampling at both sites was undertaken at the inflow to the farm, and the outflow of the holding tanks, prior to any treatment that might have been carried out. For each sampling trip, data were provided by site managers on flow rates (by volume gauging), stocking densities, fish ages, weights and feeding regimes during the period of sample collection. Prior to filtration, a sample of 100 mL was immediately decanted into Pyrex screw top conical flasks and stored in darkness for total phosphorus (TP) analysis. For suspended solids analysis, 400 mL of samples was filtered through prewashed and preweighed 47 mm glass fibre circle filter papers, using the Suspended Matter

TABLE I

Daily waste loadings and operational site data from Sites 1 and 2, 9th January–18th December 1990

Date	Loadings					Site data		
	SS	BOD	TP	TAN-N	DRP	Temp. (°C)	Fish weight (g)	Mass (t)
			(all loadings in kg t fish^{-1} day^{-1})					
Site 1								
09 Jan 90	1.3 ± 0.2	6.5 ± 0.8	0.03 ± 0.00	0.13 ± 0.03	0.04 ± 0.00	3.3	20.0	3.9
13 Mar 90	1.0 ± 0.1	2.2 ± 0.4	0.04 ± 0.01	0.13 ± 0.02	0.08 ± 0.00	4.3	26.6	5.0
05 Jun 90	11.4 ± 0.3	34.6 ± 5.3	0.83 ± 0.10	0.89 ± 0.07	0.005 ± 0.00	11.6	1.3	0.7
07 Aug 90	1.1 ± 0.1	1.3 ± 0.2	0.34 ± 0.04	1.10 ± 0.14	0.011 ± 0.00	14.7	2.9	1.6
09 Oct 90	3.6 ± 0.1	3.2 ± 0.4	0.12 ± 0.01	0.40 ± 0.05	0.02 ± 0.00	10.0	9.2	1.3
Site 2								
31 Jan 90	4.1 ± 0.2	2.6 ± 0.6	0.09 ± 0.01	0.19 ± 0.03	0.03 ± 0.00	3.1	33.6	3.1
02 Apr 90	5.8 ± 0.2	9.6 ± 1.4	0.17 ± 0.02	0.44 ± 0.05	0.06 ± 0.01	5.8	42.4	5.8
14 May 90	20.5 ± 0.4	7.0 ± 1.0	0.11 ± 0.01	0.16 ± 0.02	0.01 ± 0.00	10.1	44.2	10.1
17 Jul 90	18.9 ± 0.3	12.1 ± 1.8	0.60 ± 0.07	1.71 ± 0.15	0.004 ± 0.00	15.1	2.8	15.1
25 Sep 90	7.8 ± 0.2	6.9 ± 0.9	0.21 ± 0.03	0.36 ± 0.04	0.03 ± 0.00	9.1	21.7	9.1
18 Dec 90	2.4 ± 0.2	5.2 ± 0.8	0.09 ± 0.01	0.11 ± 0.01	0.02 ± 0.00	4.3	27.1	4.3

Legend:
Fish wt.: mean fish weight for production unit on sampling date.
Mass: total fish biomass held at site on sampling date.
Temp.: inflow water temperature.
± values represent 1 s.e.

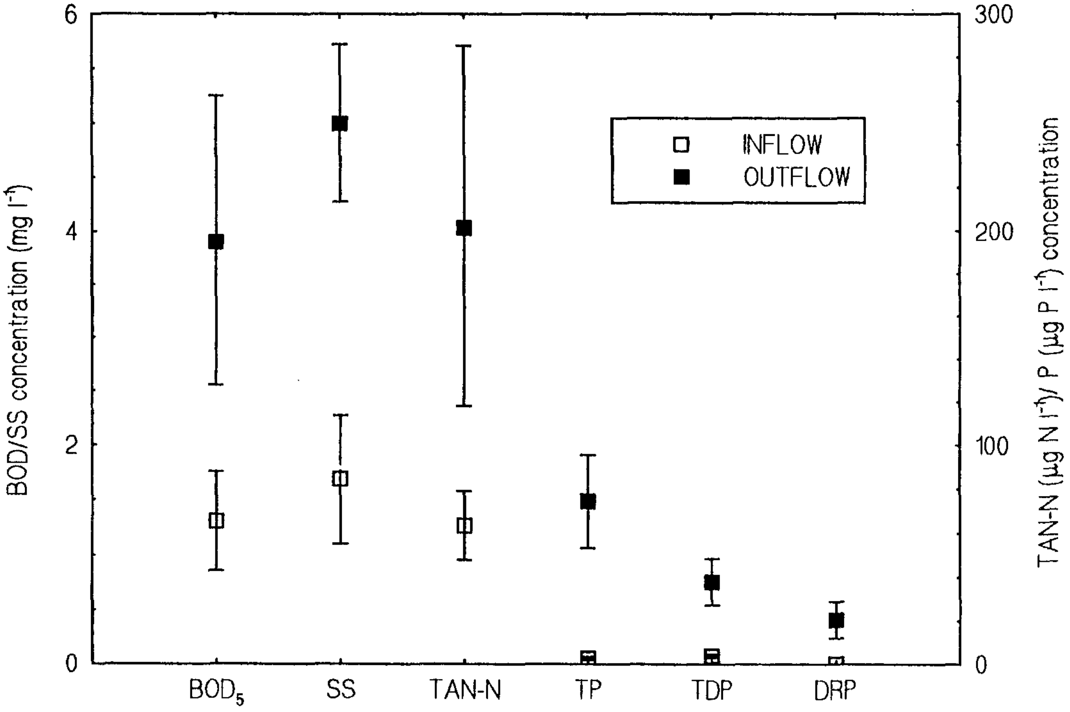

Fig. 1. Mean and standard deviation in inflow and outflow concentrations of measured variables for Sites 1 and 2); error bars represent ± 1 s.d.

Paper method (HMSO, 1980b). The filtrate was transferred to 500 mL polyethylene bottles and stored frozen for analysis of dissolved nutrient parameters. One litre bottles containing the remainder of each sample were then stored in a cool dark conditions until return to the laboratory. All other analyses were carried out on the samples obtained in one litre wide necked polyethylene bottles. Variation in inflow water chemistry for most parameters were low when compared to outflow concentrations (Figure 1); sampling at the outflow point was therefore not corrected for residence time within the farm site.

2.3. LABORATORY ANALYSIS

The preweighed filter papers used for SS analyses were dried at 105 °C for 24 hr and reweighed (HMSO, 1980b). This method has a detection limit of 0.5 mg SS L^{-1} (HMSO, 1980b). TP determinations were performed with 100 mL samples taken on site and DRP on 25 mL aliquots of filtered samples. After a sulphuric acid/potassium persulphate digestion, TP and DRP were determined with ascorbic acid as the reducing agent (HMSO, 1980a). All readings were made on a Uvikon 810 spectrophotometer using 4 cm cells with DRP results corrected for sample colour interference. TP/TDP analysis has a detection limit of 0.8 μg P L^{-1}; DRP analysis

$1.0\ \mu g\ P\ L^{-1}$. Both analyses have an error of ± 0.5%. Total ammonia nitrogen (TAN) was determined using an automated salicyalate technique (HMSO, 1982; APHA, 1987). TAN analyses were undertaken in duplicate using a microcomputer controlled Technicon II Autoanalyser BOD_5 was determined using allylthiourea for suppression of nitrification (HMSO, 1988, APHA, 1987), Samples were shaken carefully to ensure suspension of solids. Modified Pomeroy, Kirchmann, Alsterberg (PKA) reagent was used to fix the sample. Dissolved oxygen in each bottle was determined by titration to a starch-iodine end point with sodium thiosulphate. All BOD analyses were performed in duplicate. The method has a detection limit of $0.5\ mg\ O_2\ L^{-1}$, and an error of ± 2.0%. Feeds samples in use at the time of each site visit were analysed in triplicate for P content by a sulphuric acid/selenium/hydrogen peroxide digestion (Allen, 1974).

2.4. LOAD CALCULATION

All data generated from field observations and analytical procedures were stored and loadings calculated on a PC-based spreadsheet. Daily waste load was expressed as the waste loads per kg of fish on the farm, and calculated on an inflow corrected basis using the following calculation:

$$\text{DAILY LOAD (kg } [parameter]\ t\ \text{fish}^{-1}\ \text{day}^{-1}) = \frac{(C_0 - C_I)}{MASS \times TIME}$$

where

C_0 is the mean of 24 hourly outflow concentrations (mg $[parameter]$ L^{-1})

C_I is the mean of 24 hourly inflow concentrations (mg $[parameter]$ L^{-1})

Q is the mean daily outflow volume ($L\ s^{-1}$)

$MASS$ is the biomass of fish held on the day of sampling (t)

$TIME$ is 24 hr (s)

From the above calculation, annual loads were summed for each parameter from their respective daily load values as follows;

$$ANNUAL\ LOAD\ (\text{kg } [parameter]\ t\ \text{fish}^{-1}\ yr^{-1}) =$$

$$(DAILY\ LOAD\ [parameter]_a) \int_i^j M_a\, dt +$$

$$(DAILY\ LOAD\ [parameter]_b) \int_k^l M_b\, dt\ \ldots.\ \text{etc.}$$

where

a is the sample date expressed in Julian days ($a = 0$, 1st January), and is the middle of the sampling period i.e. $a = 1/2(j - i + i)$

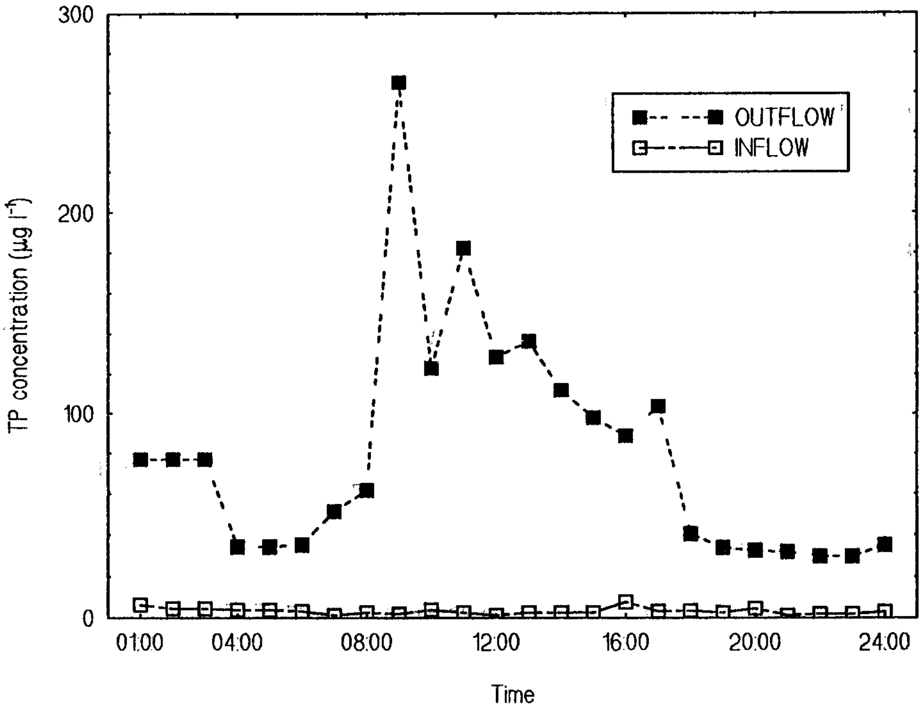

Fig. 2a.

Figs. 2(a)–(c). Diel variation in BOD_5, SS and TP concentration for inflow and outflow at Site 1 on 7th August 1990.

DAILY LOAD$_a$ is the daily load on sample data a (kg t fish^{-1} day^{-1})

t is the sampling period in Julian days, i.e. $T_a = j\text{-}i$,

M is the in biomass in the sampling period

Calculated daily and annual loads are presented below (Tables I and II, respectively).

3. Results

For all measured parameters, clear increases in concentrations occurred as the water flow passed through the farm sites (Figure 1). High variability was particularly notable in outflow measurements, correspondsing to the wide fluctuations in effluent parameter concentrations observed on a diel basis throughout the study (Figures 2a, b, c).

On a daily basis, a large of waste loads were observed for all reported parameters; a range of at least one order of magnitude was observed in almost all cases at both

TABLE II

Daily waste loading range of present study compared with other studies

Species (system)	TAN-N	DRP	SS	BOD	TP	Reference
	(all in kg t fish^{-1} day^{-1})					
R (p)				1.6–4.6		Bergheim and Selmer Olsen (1978)
B,R (t,p)	0.02–1.3	0.02–0.27	1.2–7.1	1.6[a]	0.01–0.43	Bergheim *et al.* (1982)
B,R (t,p)	0.58	0.13	3.3		0.22	Bergheim *et al.* (1984)
B (t)	0.3–0.8	0.06–0.17	0.8–0.94			Clark *et al.* (1985)
R (c)			5.5		0.16	Merican and Phillips (1985)
A (t)	0.01–0.08				0.03–0.04	Fivelstad *et al.* (1990)
A (t)			0.785		0.032	Eikebrokk and Ulgenes (1993)[b]
A (t)	0.11–1.71	0.00–0.08	1.1–20.5	1.1–34.6	0.03–0.83	Present study, Sites 1 and 2

Abbreviations: A: Atlantic salmon; B: Brown trout; R: rainbow trout; c: cages; p: ponds; t: tanks; [a] BOD_7 value; [b] estimated loads.

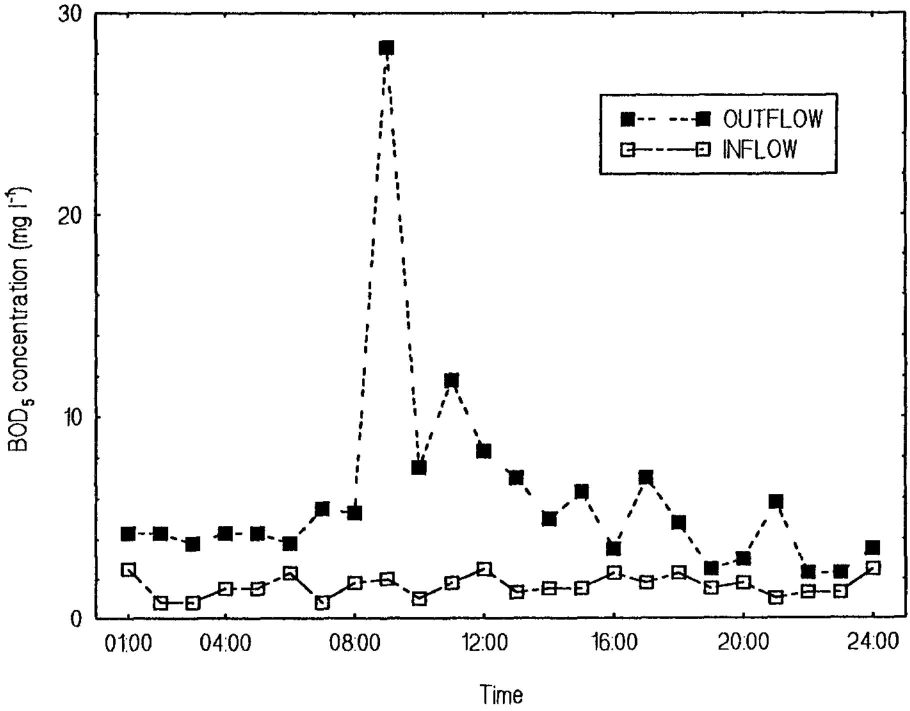

Fig. 2b.

Sites (Table I). Both sites demonstrated a strong inverse pattern between mean fish size and rate of waste output (Table I). Whilst the parameters associated primarily with solid fractions of waste i.e. SS, BOD$_5$ and TP were observed to reduce in daily load as fish size increased, at the same time the dissolved inorganic nutrient loads (TAN, TDP, DRP) were less clearly affected by such considerations (Table II).

Annual waste loadings were calculated from the daily waste loadings as discussed above (Table III). The lack of consistency between the estimates of SS output is the single major deviation in the estimates of waste losses for the two sites. The frequency of sampling used for this study is likely to have had a considerable effect upon this outcome; and in particular, the effect of the result from Site 2 on the 14th May 1990. The loss of solid material on this day was observed to be unusually high, and comparable with the early feeding stages; combined with the high biomass on site at that time, this result has had the effect of skewing the annual budget upwards.

4. Discussion

Peak daily BOD$_5$ and suspended solids loadings were mostly associated with the very earliest stages of fish development (Table I). Although the two sites

TABLE III

Annual waste loadings from Farms 1 and 2, compared with existing studies

Species	TAN-N	DRP	SS	BOD	TP	Reference
(system)	(all in kg t fish^{-1} day^{-1})					
R (t,p)	37–180				22–110	Alabaster (1982)
R (t,p)	55.5		1350		15.7	Solbé (1982)
R (t,p)	45		550		11	Warrer-Hansen (1982)
R (t,p)			300			Warrer-Hansen (1989)
R (t)					9.1–23	Ketola (1982)
R (c)					23	Penczak *et al.* (1982)
R (c)		1.9			13.5	Enell and Lof (1983)
R (c)		8.3			27	Phillips (1985)
R (t)		15.5			25.6	Foy and Rosell (1991a, b)
A (t)			245		6	Eikebrokk and Ulgenes (1993)[a]
A (t)	39.3 ± 3.8	5.0 ± 0.1	191 ± 13	410 ± 43	9.1 ± 3.3	Site 1, Present study
A (t)	20.0 ± 2.2	1.7 ± 0.1	606 ± 23	410 ± 61	10.0 ± 1.2	Site 2, Present study

Abbreviations: A: Atlantic salmon; R: rainbow trout; c: cages; p: ponds; t: tanks;
[a] theoretical load calculation.

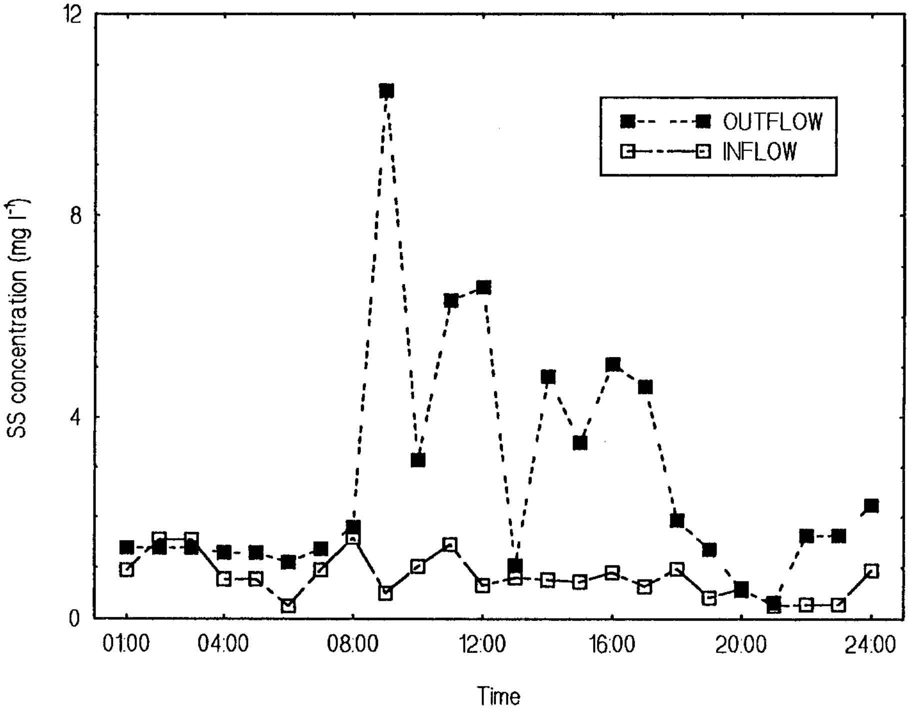

Fig. 2c.

investigated differ in mass of production by an order of magnitude, rates of waste output, expressed in terms of waste production per unit of fish biomass and with the exception of SS, were observed to be broadly similar (Table I and II). Fish farms generate waste outputs *via* feeding and the byproducts of fish activity. Rate of feeding, and therefore by extention, waste outputs, are determined primarily by reference to ration tables provided by feed manufacturers, and as a result, most freshwater sites operate similar policies with regard to feeding.

Daily loadings of SS and BOD_5 for the present study on occasions exceed the range of loadings obtained in previously reported studies (Table II). This outcome may be explained as a result of these observations including periods when fish are at very early lifestages; few studies have explicitly examined the seasonality of waste loads, although such variations have been noted (Bergheim *et al.*, 1982; Eikebrokk and Ulgenes, 1993). Indications are that larger fish generate effluent characterised by a lower BOD_5 loading, whilst small fish generate greater BOD_5 loadings per unit weight. The earliest stages of feeding for juvenile salmon require the use of small, highly friable feed particles. These particles may break up rapidly, resulting in the larger observed unit loadings of SS and BOD_5 output. Therefore, as the fish grow rapidly in size, waste loadings tend to decline. Individual events, such as the peak in SS loading (14th May 1990, Site 2), may occur from time to time as a result of atypical conditions on site, such as harvesting and grading procedures.

As expected from its relationship with metabolism, waste outputs from salmon farms were found to vary cyclically in response to fish feeding and activity periods (Figures 2a, b, c). Muir (1982) noted that in intensive salmon and rainbow trout culture, ammonia and dissolved oxygen levels showed diel or feed related peaks. Paulson (1980), Foy and Rosell (1991a) and Kelly *et al.* (1994) all emphasise the positive relationship between water temperature and TAN production. The data presented here is in agreement with these observations; a peak in TAN loadings corresponding to the periods of associated with those of higher fish activity. The peak TAN loading is more prolonged than for other parameters and extends across the whole summer period, decreasing rapidly with the onset of reduced day length and inflow water temperature in autumn (Table II).

Nutrient leaching rates differ depending upon the physical characteristics of solids produced e.g. losses of phosphorus from feed and faeces occur at different rates (Merican and Phillips, 1985; Phillips *et al.*, 1993). Hence variations in the relative qualities of the two forms of solid wastes in the effluent water will influence concentrations of dissolved nutrients. However, at the point of highest TP release, DRP outputs at both sites were at a minimum (Table II). High levels of P loss during these periods are, like BOD_5 and SS, a result of poor feed uptake and rapid particle disintegration rather than leeching directly from feed pellets, but unlike TAN outputs, appear less influences by water temperature.

Annual loadings of TAN, DRP, BOD_5, and TP for both sites in the present study are towards the lower end of the ranges reported in other studies (Table III), although most comparable work has focused on rainbow trout, rather than salmon. Operational changes to feeding methods with a lesser degree of reliance on automation have taken place in recent years in the Scottish industry. Many operators now rely to a greater on manual feeding of parr, not only to reduce feed wastage, but also to improve stock husbandry. Coupled with a move away from reliance on automated feeding, there have been considerable improvements in feed quality. Reductions in N and P content, together with higher digestibility of feed pellets have reduced the total load to the surrounding environment (Phillips *et al.*, 1993). P content of feed fell consistently through the late 1980s, from 1.7% (Phillips, 1985) to *c* 1.0% in the present study. The reduction in P loadings from this study weakly reflects this decline (Table III). However, whilst decreases in P output may be expected through the continued improvement in feed quality, improved sensitivity of feeding strategies and techniques (Thorpe *et al.*, 1990; Metcalfe *et al.*, 1992) for the purposes of improved production in freshwater production may yet to have a further impact upon levels of waste output.

5. Conclusions

Results reveal that fish farm effluent from Atlantic salmon parr production is extremely variable in nature, both during a daily and annual cycle, with much of the variation being in relation to the lifestage of the fish stocked. To attempt to characterise fish farm effluent quality on the basis of one visit is of limited use; the range of results obtained for the present study indicate that a shorter time period between monitoring visits is required to improve determination of waste outputs. This is an important consideration in planning and monitoring fish farm effluent for regulatory authorities. From the results presented, it would appear that the scale of production may have only a limited effect upon annual unit mass waste output when compared to other influences such as feeding rate fish lifestage. Little published data exists with which to compare these results, as most are generated from other salmonid species and with production systems associated with larger fish being grown to market size. The lower overall output of many waste parameters reported here mirror those expected from improved feed composition, indicating that both further improvements in feed quality and feeding techniques are the key to continued reductions in aquaculture waste production. At present a further study is being undertaken with this objective.

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