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Impact of trout aquaculture on water quality and farm effluent treatment options

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Abstract – In the context of the European Water Framework Directive, the in- and outflow water quality from 13 German trout farms, rearing mainly rainbow trout (*Oncorhynchus mykiss*) and using inflow rates between 0.03–0.80 $m^3\ s^{-1}$, were monitored for point-source pollution. The farms had a significant effect on the effluent quality and macro-invertebrate fauna in adjacent streams (saprobic index based on species assemblage and abundance was 1.56–2.10 upstream of the farms but increased to 2.06–2.37 downstream of the farms). Inflow water quality, type of rearing unit, feeding intensity (amount of feed input in relation to water resources) and effluent treatment method could be used to predict effluent quality by 50 to 88% for most water characteristics. Based on these results, different effluent treatment options were monitored for their treatment performance. Concrete sedimentation basins 11 m × 7 m × 1.2 m and 5.5 m × 3.3 m × 1.5 m (L × W × H), respectively, used for total farm effluent had little or no treatment effects. The micro-screen examined was relatively effective on particulate water components, measured as total phosphorous (TP), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD) and total suspended solids (TSS), resulting in treatment efficiencies of 29–53%, which is less than expected from data in the literature. The constructed wetland examined showed the highest treatment efficiency: more than 35% for TP, COD, BOD_5, TSS and total ammonia nitrogen (TAN). From these results and data from the literature, treatment strategies for trout farm effluents can be developed, depending on the rearing system and production intensity.

Key words: Aquaculture ecological impact / Trout farming / Effluent quality / Effluent treatment / Sedimentation basins / Constructed wetlands

Résumé – Impact de l'aquaculture des truites sur la qualité de l'eau et les traitements des rejets aquacoles. Dans le contexte de la directive cadre européenne sur l'eau, la qualité de l'eau, en entrée et en sortie, a été suivie sur 13 piscicultures allemandes de truites, élevant principalement des truites arc-en-ciel (*Oncorhynchus mykiss*) et utilisant des débits d'entrée de 0,03 à 0,80 $m^3\ s^{-1}$, pour évaluer les sources de pollution. Les piscicultures ont un effet significatif sur la qualité des effluents et la faune de macro-invertébrés des rivières voisines (l'index saprobique, basé sur l'assemblage et l'abondance des espèces, est de 1,56 à 2,10 en amont des piscicultures mais augmente en aval : 2,06 à 2,37). La qualité des entrées d'eau, le type d'unité d'élevage, l'intensité de l'alimentation (quantité de nourriture fournie en relation avec les ressources en eau) et la méthode de traitement des effluents peuvent être utilisés pour prédire leur qualité de 50 à 88 % pour la plupart des caractéristiques de l'eau. D'après ces résultats, les différentes options de traitement sont contrôlées pour leur performance. Des bassins de sédimentation en béton 11 m × 7 m × 1,2 m et 5,5 m × 3,3 m × 1,5 m (longueur × largeur × profondeur), respectivement utilisés pour les effluents totaux ont peu ou pas d'action sur le traitement des effluents. Le micro-filtre étudié est relativement effectif sur les composants particulaires de l'eau mesurés, tels que le phosphore total (TP), la demande biochimique en oxygène (BOD_5), la demande chimique en oxygène (COD) et les particules totales en suspension (TSS), résultant de 29–53 % de l'efficacité du traitement, ce qui est inférieur à ce qui était attendu d'après les données de la littérature. Le bassin de décantation mis en service montre l'efficacité la plus importante, plus de 35 % pour TP, COD, BOD_5, TSS et pour l'azote total (TAN). De ces résultats et des données bibliographiques, des stratégies de traitement des effluents de pisciculture de truites peuvent être développées selon le système d'élevage et l'intensité de la production.

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1 Introduction

The demand for aquaculture products is rising constantly worldwide (FAO 2006). In the European Union, rainbow trout (*Oncorhynchus mykiss* Walbaum) is the most important aquacultured finfish species, with a total production of more than 215 000 t in 2003 (European Commission 2006). More than 90% of European aquaculture farms are small and geographically dispersed (Varadi 2001), and the trout producing sector in particular is mainly characterized by regionally-based businesses with an average annual production of 100 t or less (MacAlister Elliott 1999).

Trout production, like any other animal production, produces wastes. Aquacultural waste, by definition, includes all materials that are not removed through harvesting (Bergheim and Asgard 1996). The principal wastes from trout aquaculture are excreta and, to a low extent, uneaten feed. Aquacultural wastes are discharged in the farm effluent if not first extracted through effluent treatment.

The effect of trout farm effluents on adjacent ecosystems is a function of the amount and type of pollutants and the assimilative capacity of the receiving system (Rosenthal 1994; Piedrahita 2003; O'Bryen and Lee 2003). Potential environmental problems that can arise from aquaculture effluents are manifold (reviewed in Sindilariu 2007), ranging from simple reactions to nutrient enrichment (like an increase in primary production) to heightened substrate embeddedness due to high TSS loads and shifts in the species community due to trophic and habitat changes downstream of fish farms.

Effluent management is required to prevent the potentially negative effects of trout farm effluents and conflicts with other users, especially in the context of the European Water Framework Directive where fish farms have to be considered as point-source polluters. Waste removal through final treatment facilities is needed (Cripps and Bergheim 2000). Different mechanical treatment methods like screens or sedimentation basins (Cripps and Bergheim 2000) or even biological treatment devices like constructed wetlands (Sindilariu et al. 2007, 2008) can be used to reduce nutrient levels in effluent.

In this study, the in- and outflow of 13 Bavarian trout farms was monitored for water quality. This is the first study to evaluate the existing impact of trout aquaculture and factors influencing the effluent quality for the region, which has the highest trout production in Germany (Brämick 2007). Additionally macro-invertebrate stream biology was assessed up and downstream of six of these farms to identify the biological effects, as this is the classic assessment tool for running water quality in Germany (Von Tümpling and Friedrich 1999). The efficiency of four treatment devices was then compared and their application in trout aquaculture will be discussed.

2 Material and methods

2.1 Monitoring and analysis of farm in- and effluents

Thirteen trout farms were examined for their inflow and outflow water quality. All farms were situated in Bavaria (Germany). Relevant characteristics of the examined farms are listed in Table 1. Six farms take their inflow water from brooks, with inflow rates of 0.10–0.80 $m^3\ s^{-1}$, while seven farms were fed by spring water, with inflow rates of 0.025–0.12 $m^3\ s^{-1}$. Farm in- and outflow water was sampled on 163 days between the end of 2005 and end of 2007.

All results presented are based on water samples collected by automated samplers situated at the in- and outflow of the sites examined (fish farm or treatment device). The samplers run for 24 h, to collect 24-h pooled samples. Every 10 min a defined water volume is collected and added to a common sampling tank. The sampling tanks were either insulated, or situated in the sampling water to maintain the collected samples at a constant, cool temperature. After the sampling period, the samples were immediately transported to the laboratory for analysis.

The water samples were analysed for the following parameters measured in mg L^{-1}: total nitrogen (TN), total ammonia nitrogen (TAN), nitrite nitrogen (NO_2-N), nitrate nitrogen (NO_3-N), total phosphorous (TP), phosphate phosphorous (PO_4-P), biochemical oxygen demand over 5 days (BOD_5), chemical oxygen demand (COD) and total suspended solids (TSS). The physicochemical properties of the water samples were determined following German standard methods for examination of water, wastewater and sludge (DIN 2006). For BOD_5 the total oxygen consumption of the original sample was assessed, including nitrification. The particulate matter in the sample was not destroyed prior to measurement.

2.2 Regression models

Factors with a potential impact on effluent nutrient concentration were recorded and integrated in a multifactor covariance model:

$$Y_{ijkl} = \mu + a\alpha_i + b\beta_j + c\gamma_k + d\delta_l + \varepsilon_{ijkl},$$

where Y_{ijkl} is the relevant effluent concentration, μ the overall effluent concentration, α_i the inflow concentration, β_j the rearing unit, γ_k the used effluent treatment device, δ_l feeding intensity in g m^{-3} and ε_{ijkl} the random residual error. Estimates of the model coefficients a, b, c, and d are given in Table 3. The factors were identified as relevant at a probability level of $\alpha < 0.05$. The residuals were tested for homogeneity and normal distribution. All statistical calculations were performed with SAS 8e. In order to integrate the relevant factors into the model, they had to be transformed or scaled as follows:

2.2.1 Rearing units

The rearing units used for fish production were classified into self-cleaning units, or non self-cleaning units (Willoughby 1999). Self-cleaning units, like concrete raceways or circular tanks, are characterized by a rapid export of suspended particles out of the system (Milden and Redding 1998; Wheaton and Singh 1999). In this study, six farms used only earthen ponds as rearing units, three farms used only concrete raceways, and the other four farms used a mix of both. The amount of concrete raceways per farm was entered into the model as scaled variable, where 1.0 stands for earthen ponds, exclusively and 2.0 for concrete raceways, exclusively. For the other

Table 1. Major characteristics of the 13 sampled trout farms.

Farm nb:	Water source	Q (m^3 s^{-1})	Feed input (f) (kg day^{-1})	Production intensity $Pi = f/Q$ (g m^{-3})	Rearing units 1 = ponds; 2 = raceways	Effluent treatment	Scaled effluent treatment
1	brook	0.100	77	8.9	1.0	sedimentation basin with fish	2.0
2	brook	0.700	575	9.5	1.0	none	1.0
3	brook	0.300	180	6.9	1.0	none	1.0
4	brook	0.350	530	17.5	1.5	none	1.0
5	spring	0.025	75	34.7	1.5	sedimentation basin with fish	2.0
6	spring	0.050	100	23.2	1.0	none	1.0
7	spring	0.120	137	13.2	1.0	sedimentation basin with fish	2.0
8	spring	0.040	20-50	5.8 – 14.5	1.0	none	1.0
9	brook	0.455	350	8.9	1.2	none	1.0
10	brook	0.800	800	11.6	2.0	sedimentation basin without fish	3.0
11	spring	0.120	260–550	25.1–53.1	1.8	sedimentation basin with fish and constructed wetland	2.2
12	spring	0.033	150–300	52.6–105.2	2.0	sedimentation basin without fish / micro-screen	3.0 / 4.0
13	spring	0.120	100–200	9.7–19.3	2.0	two consecutive micro-screens	5.0

farms the proportion of raceways compared with ponds was calculated as a fraction and added to 1.0 (Table 1).

2.2.2 Amount of feed input / production intensity

For each farm, the fish farmer noted the amount of feed input per day (f). Additionally the amount of inflow water was measured (Table 1). Flow measurement was performed with a flow meter (model HFA, Höntsch inc.), measuring the mean flow velocity. Through multiple measurements, the total amount of water could be calculated.

Consequently the production intensity (Pi) was calculated as the amount of feed input per day (f, kg day^{-1}) divided by the water inflow rate (Q, m^3 s^{-1}), [$Pi = f / (Q \times 86\,400)$]. The production intensity of the trout farms ranged from 5.8 to 105 g m^{-3}. All farms used energy rich, extruded feed.

2.2.3 Effluent treatment device used on farm effluent

Six farms used no effluent treatment, which was scaled as treatment option 1.0 for the model. Four farms used sedimentation basins, with fish stock, given as treatment option 2.0 for the model (Table 1). One of these farms used a constructed wetland, described below, for the treatment of about 20% of its total effluent. The effluent treatment of this farm was scaled as 2.2. Sedimentation basins without fish were scaled as treatment option 3.0. Another farm used a micro-screen for effluent treatment, which was scaled as option 4.0, and yet another used two consecutive micro-screens, a coarse one on the farm (as intermediate treatment) and a finer one as the final treatment, scaled as option 5.0 (Table 1).

2.3 Macro invertebrate fauna

For six farms the macro invertebrate fauna were sampled up- and downstream of the fish farm. The sampling stations for a farm were selected to have a high habitat similarity (structure, insolation and current). Downstream sampling stations were selected to have mixing between river water and trout farm effluent with no self-purification (Boaventura et al. 1997). For each sampling station a saprobic index was calculated.

The saprobic index is a scale to specify the loading of easily degradable organic matter in running waters. Saprobic index is determined from the different species of organisms present in an environment. Different species have different saprobic rates previously obtained from empirical studies. The frequency of occurrence of different species is used as a measurement of the saprobic index of a stream: the index is determined by calculating the loading (number of individuals x saprobic rate of species) that will be between 1.0 (no loading – good quality) and 4.0 (excessive loading), see also Rolaufs et al. (2004) for further information.

At each sampling station, macro invertebrates were collected by “kick sampling and collection” (DIN 2006; von Tümpling and Friedrich 1999) twice per station with a intersampling clearance time of at least one month, and identified using German standard methods for the examination of water, wastewater and sludge (DIN 2006, and after von Tümpling and Friedrich 1999). For each sampling, the saprobic index (S), formula (1), with confidence interval (SM), formula (2) was calculated following DIN nr. 38 410 in DIN (2006; von Tümpling and Friedrich 1999).

$$S = \frac{\sum_{i=1}^{n} s_i \cdot A_i \cdot G_i}{\sum_{i=1}^{n} A_i \cdot G_i} \quad (1)$$

$$SM = \pm \sqrt{\frac{\sum_{i=1}^{n} (s_i - S)^2 \cdot A_i \cdot G_i}{(n-1) \cdot \sum_{i=1}^{n} A_i \cdot G_i}} \quad (2)$$

For each species collected (i) a saprobic value (s_i) and a saprobic weight (G_i) are available in DIN number 38 410, while

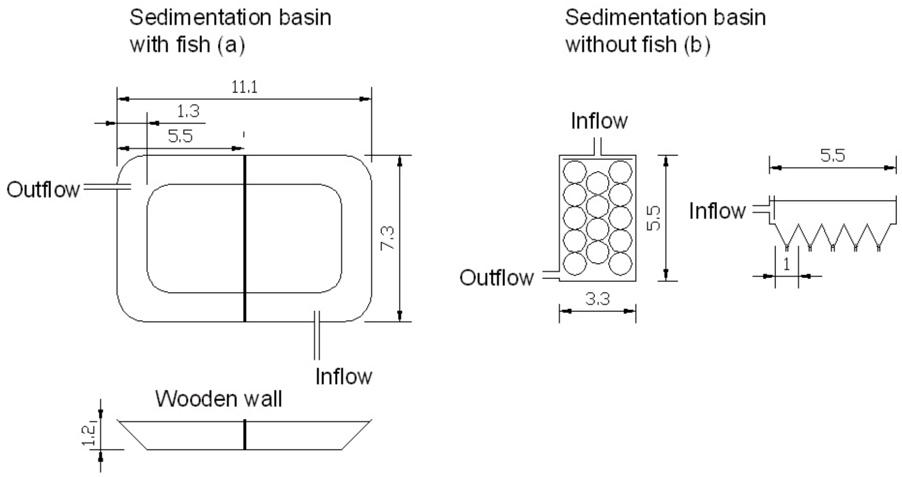

Fig. 1. Top and side view of the sedimentation basin (a) with and (b) without fish. Distances indicated in metres.

(n) is the number of species caught (represented in DIN number 38 410), and A_i is the abundance of species i, divided into abundance classes. The index is valid when $SM < \pm 0.2$ and $\Sigma A_i \geqslant 15$.

2.4 Monitoring of treatment efficiencies of effluent treatment devices

The treatment efficiency of the treatment devices was evaluated based on the water quality of the in- and outflow.

2.4.1 Sedimentation basin with fish

During the sampling period, between July and November 2006, the basin was sampled four times on three consecutive days (24-h pooled samples; $N = 12$). The sedimentation basin of 81 m^2 (69 m^3), consists of two chambers separated by a wooden wall (Fig. 1). The whole effluent (0.09–0.10 $m^3\,s^{-1}$) of a farm consisting exclusively of earthen fish ponds is treated in the basin, with an overflow rate of 0.0012 $m\,s^{-1}$. The feeding intensity (P_i) in this farm (amount of feed input) is about 8.9 $g\,m^{-3}$. A small stock ($N \approx 50$) of large irregularly fed rainbow trout is kept in the basin.

2.4.2 Sedimentation basin without fish

In the sampling period, between July and September 2007, a 24-h pooled sampling was performed once every week ($N = 9$). The basin (18.1 m^3, not including the sedimentation cones) contains a baffle at the inflow to reduce the flow velocity. Sedimentation cones have been installed on the bottom of the basin (Fig. 1). The settled sludge is removed from the basin daily, by lifting balls situated at the base of the cones and opening a drain at the bottom. An outflow of 0.030–0.040 $m^3\,s^{-1}$ from several trout production raceways is treated in this basin with an overflow rate of 0.0022 $m\,s^{-1}$. The basin is fish-free. During the sampling period, the feeding intensity (P_i) in the raceways was between 31.7 and 39.9 $g\,m^{-3}$.

2.4.3 Micro-screen as a final effluent treatment

During the sampling period, between April and October 2007, a 24-h pooled sampling was performed every second week ($N = 15$). The micro-screen examined is a drum filter with a mesh size of 63 μm (FAIVRE Sarl 120-16). It is situated at the outflow of a farm operating exclusively with raceways. After the drum filter, about 0.040 $m^3\,s^{-1}$ (50%) of the water is discharged, and 0.040 $m^3\,s^{-1}$ is recirculated by a pump discharging into a nearby raceway. During the sampling period, the feeding intensity (P_i) in the farm was about 53.8–95.1 $g\,m^{-3}$.

2.4.4 Constructed wetland

During the sampling period, between November 2005 and February 2007, the wetland was sampled on four occasions, taking into account three consecutive days each time (24-h pooled samples). Overall, one day of sampling failed resulting in a total of $N = 11$ sampling days. The constructed wetland is used to treat a part (20%) of the total farm effluent, about 0.023 $m^3\,s^{-1}$. The constructed wetland consists of a pre-sedimentation basin, a surface flow (SF) wetland and a sub surface flow (SSF) wetland (Fig. 2). The wetland has been constructed using spare fish ponds. The SSF wetland has a gravel root zone consisting of 18–32 mm gravel. In both wetlands a natural plant community has become established, dominated by *Lema* sp., *Rorippa aquaticum*, and *Mentha aquatica* in the SF wetland, and *Thypha latifolia*, *Lythium salicaria* and terrestrial grasses in the SSF wetland.

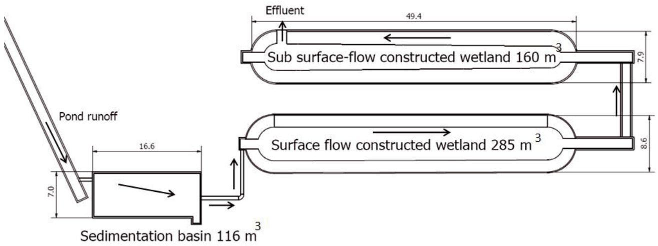

Fig. 2. Schematic function principle of the constructed wetland examined. Distances (in m).

2.4.5 Data analysis

For the treatment methods examined, differences (Δp) between inflow and outflow concentrations were calculated for each parameter as well as for each pair of simultaneous samples. The relative treatment efficiency ($\%\Delta$) was calculated for each parameter as $\%\Delta = (\Delta p/c_{in}) \bullet 100\%$, with Δp = inflow – outflow concentration in mg L^{-1} and c_{in} = inflow concentration in mg L^{-1}.

For the Δp data of each parameter a Shapiro-Wilk test for normality was performed, with a significance level of $\alpha < 0.05$. When the Δp data where normally distributed, a one sample Student t-test was performed in order to evaluate whether Δp was significantly different from 0. When normality for the Δp data was rejected, then the Wilcoxon test (signed-rank test) was used to test whether Δp was significantly different from 0 or not.

3 Results

3.1 Monitoring of farm effluents

3.1.1 Effect of fish farms on effluent parameters

Fish farming was associated with a significant increase in effluent concentration for all measured parameters compared with inflow concentrations, except for NO_3-N where a significant decrease was measured in the effluent concentration. Mean inflow and outflow concentrations are listed in Table 2.

3.1.2 Effect on macro invertebrate fauna

The saprobic index increased downstream of the trout farms, compared with the upstream index. Upstream of the farms the index was between 1.56 and 2.10 (±0.09–0.17), depending on the stream examined, while the downstream index increased to 2.06–2.37 (±0.08–0.14) (Fig. 3). However, for the farms operating with low production intensities of 8.9 and 9.5 g m^{-3}, the shift in the saprobic index between up- and downstream sampling stations was not significant. At higher production intensities the difference between up- and downstream macro invertebrate fauna was significant, as it was for the farm operating at 6.3 g m^{-3}.

Table 2. Mean in- and outflow water quality with standard deviations (*SD*), and differences (Δp) from all monitored trout farms, with the indication of significance "*" for Δp, at the significance level <0.05 (all indicated values in mgL^{-1}).

Water parameter (mg L^{-1})	Mean inflow (*SD*)	Mean outflow (*SD*)	Difference Δp (*SD*)
TN	5.35	5.79	0.44 *
	(1.37)	(1.55)	(0.85)
TAN	0.04	0.47	0.43 *
	(0.03)	(0.40)	(0.41)
NO_2-N	0.03	0.08	0.05 *
	(0.05)	(0.06)	(0.05)
NO_3-N	5.28	5.09	–0.18 *
	(1.23)	(1.25)	(0.54)
TP	0.04	0.13	0.10 *
	(0.03)	(0.10)	(0.11)
PO_4-P	0.02	0.06	0.04 *
	(0.02)	(0.05)	(0.051)
BOD_5	1.57	3.73	2.13 *
	(0.07)	(1.90)	(1.74)
COD	5.89	8.95	3.06 *
	(4.42)	(3.69)	(3.35)
TSS	6.70	6.73	0.03 *
	(14.69)	(4.47)	(14.51)

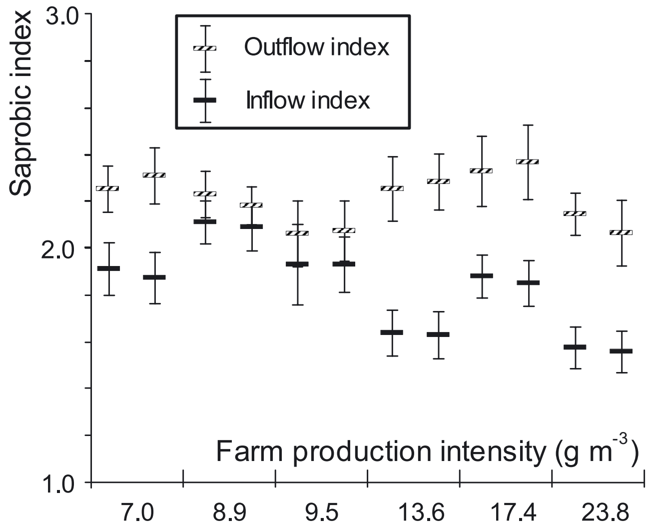

Fig. 3. Saprobic index in the farm in- and outflow depending on the feeding intensity of the six trout farms examined (two measurements per site).

3.1.3 Modelling of effluent quality

Effluent quality can be predicted to 50–88% through four main factors: amount of feed used, inflow nutrient concentration, rearing unit used and effluent treatment device. Only the predictability of TSS was lower, at about 13% (Table 3). A factor increase by one unit results in the estimated change (shown in Table 3) in the effluent parameter concentration (positive estimate = increase in concentration, negative estimate = concentration decrease).

An increase in the amount of feed used in the fish farm, resulted in a significant increase in the effluent concentration

Table 3. Estimates for the coefficients of the regression model on effluent water quality (* indicates significant estimates at the significance level $\alpha < 0.05$, p = probability value for the whole model, R^2 predictability of the whole model). Indicated values show the change in the outflow concentration in mgL^{-1} when changing the relevant regression model factor by 1 unit.

Parameter ($mg\ L^{-1}$)	μ	Inflow concentration	Rearing unit	Effluent treatment	Feeding	R^2	p
TN	–0.24	0.91 *	0.49 *	–0.08	0.0237 *	0.88	0.0001
TAN	0.05	0.37	0.02	–0.02	0.0155*	0.82	0.0001
NO_2-N	0.11 *	0.71 *	–0.04 *	–0.01	0.0006 *	0.50	0.0001
NO_3-N	–0.50 *	0.91 *	0.49 *	–0.03	0.0041 *	0.86	0.0001
TP	0.02	0.33 *	0.03	–0.01 *	0.0035 *	0.63	0.0001
PO_4-P	–0.01	0.66 *	–0.01	0.01 *	0.0016 *	0.74	0.0001
BOD_5	0.33	0.91 *	0.79 *	–0.35 *	0.0580 *	0.68	0.0001
COD	2.46 *	0.69 *	1.42	–0.64 *	0.0662 *	0.61	0.0001
TSS	8.12 *	0.73 *	–4.38 *	0.52	0.0492 *	0.13	0.0012

Table 4. Inflow and outflow water quality (mgL^{-1}) of the monitored effluent treatment devices (* indicates that the difference (Δp) between inflow and outflow is significant at the significance level $\alpha < 0.05$).

Water parameter ($mg\ L^{-1}$)	Sedimentation with fish $N = 12$			Sedimentation without fish $N = 9$			Micro-screen $N = 15$			Constructed wetland $N = 11$		
	inflow (SD)	outflow (SD)	efficiency %	inflow (SD)	outflow (SD)	efficiency %	inflow (SD)	outflow (SD)	efficiency %	inflow (SD)	outflow (SD)	efficiency %
TN	6.03 (1.31)	5.60 (0.88)	7.1	7.53 (0.58)	7.45 (0.71)	1.1	7.74 (0.64)	7.91 (0.71)	–2.2	6.23 * (1.04)	5.88 * (0.98)	6.2
TAN	0.18 (0.04)	0.18 (0.03)	0.0	0.89 (0.19)	0.88 (0.18)	0.7	1.19 (0.44)	1.23 (0.24)	–3.1	0.71 * (0.29)	0.12 * (0.10)	81.7
NO_2-N	0.06 (0.01)	0.06 (0.02)	3.3	0.02 (0.01)	0.02 (0.00)	14.4	0.041 (0.01)	0.042 (0.01)	0.0	0.02 * (0.00)	0.05 * (0.04)	–139.5
NO_3-N	5.40 (0.89)	5.04 (0.49)	6.7	6.51 (0.42)	6.34 (0.30)	2.5	6.20 (0.36)	6.16 (0.31)	0.5	5.03 * (0.64)	5.43 * (0.61)	–12.0
TP	0.07 (0.03)	0.07 (0.04)	4.6	0.31 * (0.16)	0.21 * (0.08)	32.4	0.30 * (0.15)	0.20 * (0.04)	32.8	0.17 * (0.09)	0.10 * (0.03)	37.3
PO_4-P	0.07 (0.04)	0.07 (0.04)	–2.4	0.09 (0.03)	0.09 (0.03)	–9.6	0.12 (0.05)	0.11 (0.04)	7.2	0.05 * (0.04)	0.08 * (0.04)	–42.4
BOD_5	2.63 (0.43)	2.97 (1.05)	–13.0	5.17 (0.87)	5.09 (2.24)	1.5	7.98 * (3.52)	5.92 * (3.28)	25.9	4.84 * (1.86)	2.00 * (0.72)	62.1
COD	10.86 (3.42)	11.66 (4.40)	–7.3	9.44 * (3.44)	6.97 * (2.65)	26.2	14.39 * (7.84)	10.20 * (3.90)	29.1	8.80 * (5.51)	5.29 * (3.91)	39.8
TSS	9.10 (3.51)	10.22 (4.92)	–12.23	5.63 (4.88)	3.76 (1.69)	33.2	6.31 * (3.93)	3.73 * (2.52)	40.9	4.88 * (2.11)	1.74 * (0.54)	59.4

for all measured parameters. Inflow concentration had an effect on all parameters except TAN. Self-cleaning farms released more TN, NO_3-N and BOD_5, but less NO_2-N and TSS. The effluent treatment units showed a significant effect in reducing TP, BOD_5 and COD, but they led to a slight increase in the effluent concentration for PO_4-P (Table 3).

3.2 Effluent treatment devices

In- and outflow water parameters of the examined effluent treatment devices are summarized in Table 4.

3.2.1 Sedimentation basins

The sedimentation basin with fish showed no treatment effect on any of the nutrient parameters measured (Table 4). The sedimentation basin without fish, however, showed significant treatment effects for TP and COD of 32 and 26%, respectively. No significant treatment effect was detected for any of the other parameters measured (Table 4).

3.2.2 Micro-screen

Treatment efficiency and the in- and outflow water quality of the drum filter are shown in Table 4. The micro-screen had a significant treatment effect on TP (33%), BOD_5 (26%), COD (29%) and TSS (41%). No effect was found for the other water parameters.

3.2.3 Constructed wetland

The constructed wetland had a significant effect on all measured water parameters (Table 4). The wetland had large treatment effects on TAN, TSS and BOD_5 of 82, 64 and 59%, respectively. TN, TP and COD showed lower treatment efficiencies of 6, 37 and 40%, respectively. The dissolved nutrients NO_2-N, NO_3-N and PO_4-P increased significantly in the wetland outflow by 140, 12 and 42%, respectively (Table 4).

4 Discussion

The results from in-and outflow monitoring indicate that production intensity is the main factor influencing effluent water quality and biology. From another point of view, effluent treatment is the only factor that positively influences effluent quality. The different types of rearing unit affected the various water parameters differently, leading to distinct profiles of these parameters according to farming practices. Thus an effluent treatment concept can be developed depending on the production intensity. Such a concept would recommend different treatment methods in dependence on their measured treatment efficiency, in order to maintain desired effluent thresholds.

4.1 Monitoring of farm effluents

Trout farming, and the rearing of fish with energy rich extruded feed, has a significant effect on effluent water quality. This is not surprising, as other studies have already found significant nutrient increases in trout farm effluents, at least for some of the water parameters measured (Boaventura et al. 1997; True et al. 2004; Viadero et al. 2005; Maillard et al. 2005). Also, the macro-invertebrate fauna shows a specific shift in terms of individuals and species distribution (Camargo 1994; Doughty and Mc.Phail 1995; Loch et al. 1996; Selong and Helferich 1998). This shift is more pronounced as production intensity / feed input increases (Fig. 3) (Selong and Helferich 1998). However, the actual production intensity is not always reflected by biological macro-invertebrate assessment, as production intensity is a short term figure, while the macro-invertebrate community integrates disturbances over a long period of time (at least one year). Consequently, a higher impact on the aquatic fauna can be found than the present production intensity might predict (Camargo 1994), as seen for farm 1 (Fig. 3) which had the lowest feed input but a relative high impact on the invertebrate community. This high impact might date from an earlier period or arise due to very short-term disturbances not detected by chemical water analysis in the sampling period.

There are only three factors influencing the effect of trout farming on effluent water quality: the amount of feed input, the rearing unit used and the effluent treatment. The multifactor model leads to a predictability of effluent nutrient concentration of about 50–88% for most measured parameters, except TSS that had only 13% predictability. Effects that might also influence effluent concentration, but which are not integrated in the model, include the feeding regime, the specific feed formulation, the detailed shape and water residence time of the rearing system and other farm and site specific factors.

4.1.1 Inflow water quality

Farm inflow water quality has a high impact on the effluent concentration for most water parameters. This reveals the crucial importance of taking inflow water quality into account when farm outflows are monitored, in order to accurately assess the effect of trout farming (Foy and Rossel 1991; Rennert 1994). Additionally, the use of 24-h pooled samples has the advantage of mitigating the effect of water residence time within the farm, compared with grab samples, which only analyse a momentary situation.

4.1.2 Fish feeding

Fish feeding is the only factor with an effect on all measured parameters. With increased production / feeding intensity, the effluent nutrient concentration increases. Fish feed is the only nutrient source added to the fish farming system (Bergheim and Asgard 1996). Part of the feed supplied remains uneaten and becomes feed wastes. From the ingested nutrients, the undigested part is excreted as particulate faeces (Bergheim and Asgard 1996; Cho and Bureau 1997; Green et al. 2002), containing mainly organic carbon and phosphorus (Cripps 1994; Kelly et al. 1997; Cripps and Bergheim 2000). The digested nutrients are partially retained in fish body mass (Schreckenbach et al. 2001). The rest is excreted as dissolved nutrients through the gills, mainly as ammonia, and via urine as phosphate and ammonium (Cho and Bureau 1997; Bureau and Cho 1999; Green et al. 2002; Roy and Lall 2004).

Two waste streams are emitted from trout aquaculture: the particulate matter from uneaten feed and faecal excretion, and the dissolved nutrients from gills and urea excretion. The contribution of these two streams to the final effluent to the final effluent depends on the local physical, chemical and biological conditions (Brinker 2005).

4.1.3 Rearing units

Local physical, chemical and biological conditions are influenced by the kind of the rearing units used and have a significant effect on some water parameters. The reduced release of NO_3-N and TN from ponds is most probably due to denitrification occurring in the pond sediments. Anoxic areas can occur here, with sufficient carbon sources from settled faeces enhancing denitrification (Tchobanoglous et al. 2003) of the nitrate-rich inflow water. Partial dentrification leads to increased NO_2-N release from ponds. Additionally, less BOD_5 is exported from ponds, compared with raceways, as heterotrophic digestion is one of the first processes occurring in oxygen-rich environments (Tchobanoglous et al. 2003). The reason for the higher release of TSS from ponds, compared with raceways is not clear. The most likely cause is the occurrence of flooding events prior to sampling. Through the slower speed and thus longer retention time of particles in ponds compared with those in the overflowing water, a time delay in the TSS outflow from ponds can be expected from previous flooding events not sampled in the inflow as most farms using ponds also take their water from brooks. However, other studies have also had major problems in predicting TSS outflow from trout aquaculture (Roque d'Orbcastel et al. 2008).

4.1.4 Effluent cleaning devices

The effluent treatment devices had a positive effect on the concentration of the parameters involving particulate matter, TP, BOD_5 and COD (Table 3), see also Cripps and Bergheim (2000). With increased efficiency and technical improvement of the treatment unit, the effluent concentration decreased. Only for TSS, where the greatest effect would be expected with mechanical treatment (Cripps and Bergheim 2000), was no effect found. Probable over- and underestimation of TSS occurred in the water sampling due to insufficient mixing of the effluent (Brinker et al. 2005a), and the occurrence of flooding events have an high impact on the overall predictability of TSS export from aquaculture farms.

For phosphate (PO_4-P), the treatment devices had a negative impact. The leaching of PO_4-P from particulate phosphorous in trout faeces is very high, especially during the first 24 h (Stewart et al. 2006). Sedimentation basins (Cripps and Bergheim 2000) and constructed wetlands therefore particularly lead to increased PO_4-P leaching (Sindilariu et al. 2007, 2008).

4.2 Examined treatment devices

Treatment efficiency increased from the sedimentation basin with fish to the sedimentation basin without fish and was better still when using the micro-screen and the constructed wetland.

4.2.1 Sedimentation basins

Sedimentation relies on the density differences between particulate waste and the surrounding water (Cripps and Kelly 1996). The settlement velocity of suspended solids depends on particle surface and dimensions, their specific weight and the flow velocity of the surrounding water (Tchobanoglous et al. 2003). Baffles are often incorporated to promote quiescent conditions (Cripps and Bergheim 2000).

The sedimentation basin with fish was well designed (Fig. 1). The incorporation of a baffle, promoting quiescent zones, and a low overflow rate of 0.0012 m s^{-1}, much lower than the recommended flow velocity of 0.017 m s^{-1} (Henderson and Bromage 1988), should lead to effective particle retention. However, the presence of fish, especially when fed, leads to high re-suspension rates of already settled particles and additional nutrient leaching (Stewart et al. 2006). No treatment effect of the basin could thus be shown. Nevertheless, sedimentation basins with fish were used in four of the 13 fish farms monitored.

The sedimentation basin without fish had a higher overflow rate of 0.0022 m s^{-1} (Fig. 1). However, in this case significant treatment effects were found for TP and COD. Additionally, for this basin, rapid separation and removal of settled sludge from the primary flow was achieved through regular flushing of the sedimentation cones, thus avoiding high re-suspension and leaching rates of the settled nutrients (Lefebvre et al. 2001; Stewart et al. 2006). The use of sedimentation is not inherently wrong, as highly effective separators have been successfully applied (Lawson 1995), but sometimes the application is inadequate (Henderson and Bromage 1988; Cripps and Bergheim 2000).

Table 5. Total suspended solid (TSS) treatment efficiencies (%) of rotating micro-screens reported in literature.

Mesh size (μm)	Lower efficiency	Upper efficiency	Source
60	19	91	Bergheim et al. (1993)
30/60	10	99	Wedekind (1996)
80	70	75	Bergheim et al. (1998)
80	90	99	Bergehim et al. (1998)
80	65	87	Brinker and Rösch (2005)

4.2.2 Micro-screen

The micro-screen we examined had higher treatment effects than the sedimentation basins. Here additional significant effects were measured on BOD_5 and TSS. The screen treatment effect for TSS was much lower than the treatment efficiency reported in the literature (Table 5). This can be explained by regularly occurring leakages on the filter screen, a slightly undersized drum filter compared with the treated water volume and the recirculation of a part of the screen water leading to an accumulation of fine untreatable particles (Chen et al. 1993). Treatment efficiency could be improved with a larger screen, the addition of binder to feed (which would make a large improvement in particle size within the farm) and in screening efficiency (Brinker et al. 2005c), and the application of a finer screen mesh size; though such improvement would lead to much higher treatment costs (Wedekind 1996).

4.2.3 Constructed wetland

The constructed wetland had the highest treatment efficiency compared with the other treatment units. The wetland provided, in addition to mechanical sedimentation and filtration, a highly effective biological treatment of TAN and BOD_5 (Table 4) (Schulz et al. 2003; Sindilariu et al. 2007). Only for TP was the treatment efficiency in the same range as the sedimentation basin without fish and the micro-screen. TP is only retained in the wetland, and no effective extraction of phosphorous from the wetland occurs, as extraction through plant growth is of minor importance in highly loaded wetlands (Tanner and Sukias 1995; Brix 1997; Stottmeister et al. 2003; Vymazal 2005). High leaching rates of PO_4-P from the trapped particulate phosphorous therefore occur in the wetland, as the precipitation potential of the filter matrix is limited and quickly saturated (Arias et al. 2001; Del Bubba et al. 2003; Seo et al. 2005). The significant increase of NO_2-N and NO_3-N is mainly due to partial nitrification of the oxygen-rich inflow water (outflow oxygen content from a trout farm is usually around 80%), which is one of the most important treatment effects of constructed wetlands (Platzer 1999; Stottmeister et al. 2003; Sindilariu et al. 2008). A part of the NO_3-N increase is most probably denitrified in anoxic areas of the wetlands. This could explain the TN treatment effect, which can not be completely attributed to mechanical treatment of particulate nitrogen. One drawback of SSF constructed wetlands is the short service lifetime of the root zone filter, especially when used for the treatment of high hydraulic loads of particle-rich farm effluents with no mechanical pre-treatment (Sindilariu et al. 2008).

4.3 Strategies for effluent improvement

With increasing production intensity, effluent treatment efficiency must also increase to undercut potential pollution thresholds and remain below critical concentrations. The kind of effluent treatment device is dependent on the effluent characteristics (influenced by the production intensity and the type of rearing units used) and the treatment efficiency of the particular effluent treatment device. Sedimentation basins with fish make no sense as they provide no significant treatment effect (Table 4), mainly due to disturbances produced by the fish. Sedimentation basins without fish are suitable for low intensity production, providing a treatment effect for TP, COD/BOD and possibly TSS (Table 4). Production intensity in these farms can therefore be slightly increased without outflow concentrations exceeding the thresholds for TP and COD/BOD, which are the most important effluent characteristics limiting production intensity in Germany (Sindilariu 2007). The application of micro-screens as a final effluent treatment device offers the possibility of higher production levels with the same inflow, plus improved treatment efficiency compared with sedimentation (Table 4). Additionally, the micro-screen treatment efficiency can be further improved through the application of special feed additives to increase the faecal particle size (Brinker et al. 2005b,c), improvement of the screening effect, and the use of smaller screen mesh size (Wedekind 1996).

Mechanical treatment devices like sedimentation basins and screens are limited in their treatment effect on BOD, as only about 80% of BOD is particle-bound (Cripps and Bergheim 2000) and highly soluble, and on TAN for which these treatment devices have no effect. A possible solution to reduce dissolved BOD and TAN are constructed wetlands, which provide treatment efficiencies up to 60–80% for BOD and TAN respectively (Table 4, Sindilariu et al. 2008). Therefore, combining constructed wetlands with a mechanical pre-treatment could provide effective effluent improvement for intensive production sites. And thus, enable farms to meet highly stringent environmental thresholds, as constructed wetland ideally complement mechanical treatment devices and provide a supplementary biological treatment especially for BOD and TAN.

5 Conclusion

Trout aquaculture has an impact on the effluent quality and biological status of the receiving environment. The strength of the effect is dependent on the amount of feed input, the type of rearing units used in the farm and the type and efficiency of the effluent treatment system.

Effluent treatment efficiency increases from sedimentation basins with fish, which show no treatment effect, to sedimentation basins without fish and then to micro-screens and constructed wetlands, which have an effect on all measured effluent characteristics.

The specific effluent treatment needed depends on the effluent nutrient thresholds, the production intensity, the rearing system used and the efficiency of potential treatment devices. However, other features apart from treatment efficiency need to be taken in account, like yearly costs, area required, specific head loss and other crucial aspects.

A detailed cost calculation for the different treatment possibilities is needed in order to facilitate the decisions of trout producers to effectively choose and apply effluent treatments.

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