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Performance Characteristics of Four Biological Filters and the Development of a Filter Sizing Procedure

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by

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ABSTRACT

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The systems examined were two submerged gravel filters of different volumes, a trickle filter with two types of plastic media and a upwelling fluidized bed. The large gravel filter (LGF) maintained the best water quality (mean=370 $\mu g \cdot L^{-1}$ NH3-N) at the highest fish density (160 $kg \cdot m^{-3}$). At the same density, the small gravel filter (SGF) had higher ammonia levels (mean=661 $\mu g \cdot L^{-1}$). The SGF had one third the media surface area (SA) of the LGF (118 vs 328 m^2), but was able to attain ammonia removal rates 3 times that of the LGF (SGF=0.22 g vs LGF=0.07 g NH3-N$\cdot m^{-2}$ SA$\cdot$day^{-1}). The trickle filter (TF) had one quarter the media surface area of the LGF (80 vs 328 m^2), and was able to maintain removal rates almost five times that of the LGF (TF=0.38 g vs LGF=0.07 g NH3-N$\cdot m^{-2}$ SA$\cdot$day^{-1}). No difference in nitrification abilities were detected between the two types of plastic media tested (Tripacks and Ballast Rings). The fluidized bed (FB) was not able to maintain acceptable ammonia levels (mean=948 $\mu g \cdot L^{-1}$) at any fish density tested (36-72 $kg \cdot m^{-3}$). From the data of all systems, except the fluidized bed (FB), a series of equations were developed to predict; a) the rate of ammonia production at various feed levels, b) influent ammonia levels and c) the rate of ammonia removal at various feed levels.

Key words: biofilters; recirculating systems; water quality; ammonia removal; ammonia production; Arctic charr; Salvelinus alpinus; aquaculture; water filtration.

RÉSUMÉ

Vandenbyllaardt, L.J., and M.J. Foster. 1992. Performance characteristics of four biological filters and the development of a filter sizing procedure. Can. Tech. Rep. Fish. Aquat. Sci. 1854: iv + 21 p.

On a étudié deux filtres de gravier submergés de volumes différents, un filtre percolateur (FP) comportant deux types de plastique différents et un lit fluidisé à courant ascendant. Le grand filtre de gravier (GG) a maintenu la meilleure qualité d'eau (moyennne=370 $\mu g \cdot L^{-1}$ NH3-N) à la densité de poissons la plus élevée (160 $kg \cdot m^{-3}$). A la même densité, la concentration d'ammoniac était plus élevée avec le petit filtre de gravier (PG) (moyenne=661 $\mu g \cdot L^{-1}$). La surface filtrante (SF) du PG représentait le tiers de celle du GG (118 vs 328 m^2), mais pouvait atteindre un taux d'élimination de l'ammoniac trois fois plus élevé que celui obtenu avec le GG (PG=0.22 g vs GG=0.07 g NH3-N$\cdot m^{-2}$ SF$\cdot$jour^{-1}). La surface filtrante du filtre percolateur (FP) était le quart de celle du GG (80 vs 328 m^2), mais l'élimination de l'ammoniac s'est maintenue à un niveau presque cinq fois plus élevé que celui obtenu avec le GG (FP=0.38 g vs GG=0.07 g NH3-N$\cdot m^{-2}$ SF$\cdot$jour). Aucune différence du pouvoir de nitrification n'a été notée entre les deux types de plastique étudiés (Tripacks et Ballast rings). Le lit fluidisé n'a pas pu maintenir un niveau d'ammoniac acceptable (moyenne=948 $\mu g \cdot L^{-1}$) aux densités de populations de poissons étudiées (36-72 $kg \cdot m^{-3}$). A partir des données recueillies sur les filtres, à l'exception du lit fluidisé, un série d'équations ont été formulées pour prévour: a) le taux de production d'ammoniac à différents niveaux alimentaires, b) la concentration d'ammoniac arrivant de filtre et c) le taux d'élimination d'ammoniac à différents niveaux alimentaires.

Mots-clés: filtres biologiques; systémes de recirculation; qualité d'eau; élimination d'ammoniac; production d'ammoniac; Salvelinus alpinus; l'omble chevalier;aquaculture; filtration d'eau.

INTRODUCTION

The types of biological filters used in hatcheries are extremely variable. Designs vary from upwelling and downwelling submerged filters to trickle filters, activated sludge systems and extended aeration systems (Liao and Mayo 1972). In addition to the physical differences, operational characteristics such as flow rates, temperature and dimensions also vary between systems. As a result, performance of these systems under similar fish loads may also vary.

The objectives of this study were to monitor the ammonia removal abilities of four different biological filtration systems. Two of the systems were downwelling gravel filters of different volumes (LGF, SGF). The third was a trickle filter (TF) with two types of commercially available plastic media, and the fourth was an upwelling filter with small plastic beads as substrate (FB).

Performance and operating characteristics of each system were compared at similar fish densities and feeding rates. A series of predictive equations were developed to size filters, determine ammonia levels and filter performance at various feeding rates.

METHODS AND MATERIALS

SYSTEM SPECIFICATIONS

Rearing units

The filtration experiments were conducted at the Department of Fisheries and Oceans, Rockwood Aquaculture Research Centre, located north of Winnipeg, Manitoba. Fish rearing units for all systems were 1.83 m diameter fiberglass tanks, containing 1.5 m^3 of water at 7°C.

Gravel filters

Both the large gravel filter (LGF) and the small gravel filter (SGF) were submerged downwelling filters (Fig. 1). Water is gravity fed from the rearing units to the filter's settling chamber, which overflows to enter the gravel bed. Water is drawn through the gravel by a 1/3 hp pump and returned to the rearing unit through a spray bar.

The LGF had a rectangular filter bed (1.65 x 1.43 x 1.29 m), and the SGF had a circular filter (d=1.52, h=0.61 m). Total filter volumes were 2.75 m^3 and 0.93 m^3, for the LGF and SGF respectively. LGF contained 1.75 m^3 of gravel providing 328 m^2 substrate surface area. SGF had 0.75 m^3 gravel and 118 m^2 of substrate surface area (Table 1). The bottom 0.15 m of each filter bed contained 3.8 cm diameter granite gravel (106 $m^2 \cdot m^{-3}$ specific surface area). The remainder of the filter contained 2.0 cm diameter granite gravel. Both filters had similar recirculation rates (96 and 84 $L \cdot min^{-1}$). In terms of water exchange rates (Kraul et al. 1985) the LGF, SGF and TF had similar dilution rates. The SGF received 7% and the TF 17% more water on a daily basis than the LGF.

During the final loading phase of the SGF, a mat of debris began to develop on the filter bed surface. To alleviate this problem 50 L of coarse gravel (4.4 cm) was added to the filter to reduce the depth of free standing water from 13 to 5 cm. This gravel provided an additional 5 m^2 of substrate surface area. A spray bar was also added to the filter to create a rapid circular flow of water over the gravel in an attempt to reduce settling and enhance flushing of the particulate material.

Plastic media trickle filter (TF)

This system consisted of two trickle towers, each containing different types of clean plastic media. The first tower contained 120 L of the 2.5 cm diameter Tripacks (Fabricated Plastics Ltd.). The other contained 220 L of the 2.5 cm diameter Glitch Ballast Rings. The Tripack is spherical in shape and has a specific surface area of 283 $m^2 \cdot m^{-3}$. The Ballast ring is cylindrical and has 212 $m^2 \cdot m^{-3}$ specific surface area. The total surface area present in the Tripack filter was 33 m^2, while the Ballast filter contained 47 m^2 (Table 1).

Water was drawn from the centre of the rearing unit to the towers by a 1/3 hp pump. Water flow to each tower was maintained at constant and identical rates by a series of valves. Diffusers on each tower (r=0.31 m) were used to ensure an even distribution of water through the filter beds. The towers were situated at the top edge of the fish tank, so that water leaving the towers returned to the rearing unit by gravity (Fig. 2).

Fluidized bed (FB)

The fluidized bed (FB) consisted of a double drain system which collected particulate material and a small upwelling filter for nitrification (Fig. 3). Water was airlifted from the drain system to a flow divider where approximately 50% of the flow was returned to the tank. This returning water was aerated, but not filtered. The remaining water entered the bottom of the filter bed (0.9 x 0.5 x 0.4 m), flowed upward through the filter, and returned to the rearing unit. All flow other than the original airlift was gravity flow.

The operational conditions for the FB filter were changed during the experimental period. A 3/4 hp compressor was used to drive the airlift pump for the first three months of the experiment, and was replaced by a 3/4 hp blower for the final four months. The second operational change was to redesign the filters inflow.

Initially water from the airlift pump gravity fed through a 4 cm diameter pipe into the bottom of the filter bed. To enhance water distribution within the filter bed, a length of pipe with two openings was added. This pipe extended the full length of the bed. The first opening occurred in the middle of the filter and was 1.3 cm in diameter. The second was at the end of the filter bed and was 1.9 cm in diameter (Fig. 3b). Both of these designs were operated with the blower as the air source.

WATER QUALITY

Water quality and flow rates were monitored on a weekly basis. Ammonia levels (NH3-N) entering and leaving the filter beds were measured in all systems. Samples were collected between 1200 hrs and 1300 hrs. Feeding began at 0830 hrs and continued through 1600 hrs, with the daily ration presented in four or five meals. The two gravel filters (LGF and SGF) were backwashed on a 14 day cycle. Weekly samples from these systems were collected on the 4th and 11th day after backwashing. The fluidized bed was backwashed every Monday and Friday, with samples collected on Wednesday. The trickling filters (TF) were not backwashed on a regular basis.

Ammonia levels (NH3-N $\mu g{\cdot}L^{-1}$) were determined according to the method of Stainton et al. (1977), using a Baush and Lomb Spectronic 21 spectrophotometer. Nitrification efficiencies of the filters were calculated as the amount of ammonia removed per square metre of the substrate surface area per day (g NH3-N$\cdot m^{-2}\cdot day^{-1}$). Dissolved oxygen was originally monitored, but sampling was discontinued due to equipment problems.

FISH GROWTH

Initially the LGF, SGF and TF were loaded with 752, 748 and 738 Arctic charr respectively, with a mean weight of 74 grams. Initial fish density was 37 $kg{\cdot}m^{-3}$. All fish originated from a single anadromous by anadromous cross. At approximately two month intervals, additional charr were added to the gravel filters (LGF and SGF) to increase ammonia loading. Fish weights were adjusted to ensure equal densities within the two tanks.

Ammonia loading in the trickle filter (TF) and the fluidized bed (FB) were allowed to increase more slowly, simply as a result of fish growth. The fluidized bed was loaded with 2,382 Tagwerker rainbow trout (Oncorhynchus mykiss), with a mean weight of 11 grams, resulting in a density of 17.5 $kg{\cdot}m^{-3}$.

Fish were sampled once a month to determine growth rates and food conversion efficiency. A minimum of 200 charr from each tank were batch weighed to estimate mean weights. Approximately 300 rainbow trout were batch weighed from the fluidized bed. Mortalities occurring during the previous month were subtracted from the total number of fish, and new total weights and densities were calculated. Daily rations were adjusted and calculated to 80% of the table ration. (Leitritz 1980). A commercially available trout food (Martin Feed Mills, Trout Grower Diet) containing an estimated 52% crude protein and 15% crude fat was presented to both the charr and rainbow trout.

RESULTS

GENERAL

Influent ammonia levels of the large gravel filter (LGF), small gravel filter (SGF) and the trickle filter (TF), during the initial loading period were quite variable (Fig. 4a). The LGF was the only system to begin the experiment with an established and active nitrification community. As a result it maintained the lowest ammonia levels. The SGF maintained somewhat higher ammonia levels, but these levels began declining as the nitrification community became fully established. Approximately 21 days were required for the community to become fully established. Ammonia levels within the TF reached extremely high levels during the initial period (Fig. 4a). This was primarily due to a technical problem. The inflow of make-up water was not constant due to clogging of the pipes. This problem was solved and did not recur. The establishment of a nitrification community within the TF required approximately 42 days.

Generally, influent ammonia levels declined during the initial loading phase as the nitrification communities became established within the SGF and TF. Within the LGF, with its established community, influent ammonia levels increased and decreased in a cyclic pattern (Fig. 4a). This cycling coincided with this systems 14 day backwash schedule. Typically, ammonia levels peaked several days after each backwash. By the next sample (11 days after backwash) ammonia had dropped to low levels. This cycling continued during the second loading phase, but with reduced amplitude, and was not observed during the final loading phase.

As happened in all systems, influent ammonia levels increased with increasing fish load (Fig. 4a). Levels remained acceptable ($<600\ \mu g{\cdot}L^{-1}$) in all systems except during the final loading phase of the SGF, where water quality declined substantially. Ammonia levels averaged 721 $\pm$ 46 ($\pm$ se) $\mu g{\cdot}L^{-1}$, water in the rearing unit became turbid and the fish did not feed normally. At this high fish density (135 $kg{\cdot}m^{-3}$), and heavy feeding rate (1.122 $kg{\cdot}day^{-1}$), a mat of debris began to accumulate on the filter bed. To alleviate this problem coarse gravel and a spray bar were added to the filter. The increased movement of water over the filter bed enhanced flushing and reduced the rate of mat development. Water clarity improved, the fish resumed feeding and ammonia levels declined to previous levels (590 $\pm$ 43 $\mu g \cdot L^{-1}$).

Ammonia removal, on a volume basis ($\mu g \cdot L^{-1}$), for the LGF and SGF follow an asymptotic relationship with influent ammonia levels (LGF: F=396.56, df=27, P<0.0000, SGF: F=21.47, df=21, P<0.0005) (Fig. 5). Within both systems ammonia removal appears to be approaching its maximum level. The high degree of variability for the SGF may be due in part to the initial bacterial colonization phase and the development of debris on the filter bed. Both of these conditions would result in less than optimal ammonia removals.

In contrast to the gravel filters (LGF and SGF), ammonia removal ($\mu g \cdot L^{-1}$) for the TF did not vary asymptotically with influent ammonia levels. As influent levels increased there was no change in removal for the Tripack media, while removal for the Ballast rings declined slightly (Fig. 5). It appears that this system has already reached its maximum ammonia removals, and that removals may be declining as influent ammonia levels increase.

The amount of ammonia removed per square metre of media surface area (g $NH3\text{-}N \cdot m^{-2}$ $SA \cdot day^{-1}$), increased with each increase in fish load for both gravel filters (LGF and SGF) (Fig. 6). The actual rate of removal depends on the media surface area (SA) present within a particular filter. The SGF had approximately one third the surface area of the LGF (118 vs 328 m^2 SA). As a result, under the same fish loads (final density 160 $kg \cdot m^{-3}$), the SGF's rate of ammonia removal per media surface area, was on average three times that of the LGF (LGF mean=0.07 $\pm$ 0.01 g, SGF mean=0.22 $\pm$ 0.02 g $NH3\text{-}N \cdot m^{-2}$ $SA \cdot day^{-1}$).

For the plastic media trickle filter (TF), where fish load was allowed to increase slowly, simply as the result of fish growth, the rate of ammonia removal also gradually increased (Fig. 6). Once nitrification began, removal rate increased for seven weeks and then maintained a plateau of approximately 0.45 $\pm$ 0.03 g $NH3\text{-}N \cdot m^{-2}$ $SA \cdot day^{-1}$ (Tripack and Ballast towers combined) for the remaining 16 weeks of the experiment, even though fish load continued to increase from 65 to 110 $kg \cdot m^{-3}$.

The TF, with the towers combined, contains 80 m^2 of media surface area, which is approximately one quarter the surface area of the LGF (80 vs 328 m^2 SA). Under slightly lower fish densities (final density TF=110, LGF,SGF=160 $kg \cdot m^{-3}$), the combined rate of ammonia removal was on average five times that of the LGF (LGF mean=0.07 $\pm$ 0.01 g, TF mean=0.38 $\pm$ 0.03 g $NH3\text{-}N \cdot m^{-2}$ $SA \cdot day^{-1}$).

In comparing the rate of ammonia removal between media types (Tripack and Ballast rings) (Fig. 6), there was no significant difference per square metre of surface area (F=1.18, df=45, P=0.2827). On a volume basis (per cubic metre of media), the Tripacks were able to remove approximately 15 $\pm$ 7% more ammonia than the Ballast rings, the difference was however not significant (F=1.40, df=45, P=0.2429).

Over the entire experiment the LGF maintained the best water quality, followed by the SGF and TF (LGF=230 $\pm$ 26, SGF=484 $\pm$ 46 and TF=537 $\pm$ 28 $\mu g \cdot L^{-1}$ ($\pm$ se) mean ammonia level). Mortality during the six month experiment was low in all systems (LGF=5, SGF=6 and TF=11 fish).

FLUIDIZED BED (FB)

The change in air supply from compressed to blown air resulted in a significant increase in mean flow rates (F=88.11, df=17, P<0.001. Flows increased from 11 $\pm$ 1 to 26 $\pm$ 1 $L \cdot min^{-1}$. The increased flow of water through the filter bed produced a significant decline in mean influent ammonia levels (Fig. 7a), from 1209 $\pm$ 90 to 809 $\pm$ 80 $\mu g \cdot L^{-1}$ (F=11.58, df=17, P<0.01). As flow rates increased, the actual amount of ammonia removed per litre declined significantly (F=19.18, df=17, P<0.001) (Fig. 7b). The increase in flow did not produce a significant difference in ammonia removal rates (F=1.92, df=17, P=0.8451) (Fig. 7c).

Within each flow regime, the amount of ammonia removed ($\mu g \cdot L^{-1}$) depends not only on flow rate (Fig. 8a), but also on influent ammonia levels (Fig. 7b). As ammonia levels increased, the amount removed increased in a linear fashion;
Ammonia Removed ($\mu g \cdot L^{-1}$)=b Influent Ammonia Level ($\mu g \cdot L^{-1}$) + a

	df	F	Prob>F	b	a
low flow	6	24.51	0.00428	0.69	168.35
high flow	9	19.56	0.00222	0.42	125.85

The rate at which influent ammonia was removed (slope), during low flow was significantly greater (F=45.56, df=16, P<0.001), than for the high flow (Fig. 7b). For a given influent ammonia level, the low flow/high retention time condition is able to remove a greater percentage of the influent ammonia than the high flow/low retention time condition (77 $\pm$ 7 vs 59 $\pm$ 3 %). In terms of daily ammonia removal however, the low flow condition removed approximately half as much ammonia as did the high flow condition (0.13 g VS 0.23 g $NH3\text{-}N \cdot m^{-2}$ $SA \cdot day^{-1}$).

The second operational change of redesigning the filters inflow did not produce any significant changes in influent ammonia levels (F=0.10, df=16, P=0.7648), in the amount of ammonia removed per litre (F=1.89, df=16, P=0.1849) or the removal rate per media surface area (F=1.36, df=16, P=0.2614), in comparison to the previous conditions observed during the high flow rates.

Each of the variables which influence ammonia removal were evaluated. However, in a system such as this, where flow rates and influent ammonia levels are not constant, a more useful approach would be to combine these variables in the analysis. Multiple regression analysis indicates that there is a significant relationship between ammonia removal and the variables of flow rate and ammonia concentration (F=80.65, df=23, P<0.0001), in the form;

Ammonia Removal ($g \cdot m^{-2} \cdot day^{-1}$) = 541.23 - 18.51 Flow Rate ($L \cdot min^{-1}$) + 0.51 Influent Ammonia Level ($\mu g \cdot L^{-1}$).

The overall mean ammonia level was 948 $\pm$ 63 $\mu g \cdot L^{-1}$, with levels exceeding 1300 $\mu g \cdot L^{-1}$ on several occasions. Mortality was high, with over 600 fish dying in a six month period.

FISH GROWTH

The fish in all filtration systems grew significantly during the experiment (Fig. 9). Initial mean weights in the systems containing charr (LGF,SGF,TF) was 74 g. Final weights in the LFG were 243 $\pm$ 9, in the SGF were 227 $\pm$ 9 and 230 $\pm$ 8 g ($\pm$ se) for the TF. During the entire experiment there was no significant difference in the specific growth rates between these systems (F=0.06, df=17, P=0.9387). The rainbow trout in the fluidized bed (FB) grew from 15 to 122 g.

At the end of the experiment the size distribution of the charr were not significantly different among the filter systems. For a Kolmogorov-Smirnow two sample test, the test statistic for each comparison; LGF vs SGF, LGF vs TF, and SGF vs TF were 0.088, 0.118 and 0.113 all having P>0.10. The feed conversion efficiencies of the three systems were very similar, ranging from 1.09 to 1.19.

AMMONIA PRODUCTION AND REMOVAL

Ammonia production

Within the gravel filter systems (LGF, SGF), influent ammonia levels increased exponentially with feeding rate (Fig. 10a). Ammonia levels in the trickle filter (TF) also increased after the initial bacterial colonization phase. Ammonia levels in the fluidized bed (FB) did vary with feeding rates but with a negative slope:

(1) LN Influent NH3-N ($ug \cdot L^{-1}$) = a + b Daily Feed (kg)

	df	F	Prob>F	SA	b	a
LGF	28	69.58	0.0000	328	3.43	-1.14
SGF	22	43.67	0.0000	118	3.66	-1.04
TF	19	40.33	0.0000	80	5.90	-4.03
FB	19	10.02	0.0054	100	-1.73	8.44

The rate at which ammonia level increased with increasing feed rates (b), depended on the media surface area within the filter bed. The greater the surface area present, the lower the influent levels and the slower the rate at which influent ammonia increased with increasing feed (Fig. 10a). This relationship between the rate of influent ammonia level increase (b=slope) and media surface area (SA) can be used to predict rates of ammonia increase for gravel filters of other sizes (between 118-328 m^2 SA) by the following;

(2) slope = 5.59 - 0.007 Media Surface Area (SA)

These estimated rates of ammonia increase are very general as the prediction is based only on two systems (LGF,SGF). In a more detailed study with a larger number of filter systems examined this relationship would be more accurately described. Nevertheless I will proceed with these predictions to illustrate the development of the sizing procedure.

The first step is to determine the filter size (media surface area) in question and calculate an estimated 'slope' (formula 2). The estimated 'slope' can then be inserted into a standardized formula (3), derived from formula (1), to determine the expected influent ammonia level for particular filter size and feeding rate.

e.g. media surface area = 200 m^2 SA
daily feed = 1.1 kg

slope = 5.59 - 0.007 Media Surface Area
= 5.59 - 0.007 (200)
slope = 4.19

(3) LN Expected Influent NH3-N ($\mu g \cdot L^{-1}$) = b Feed (kg)
= 4.19 (1.1)
LN Expected Influent NH3-N ($\mu g \cdot L^{-1}$) = 4.61
Expected Influent NH3-N = 100 $\mu g \cdot L^{-1}$

The total amount of ammonia produced ($g \cdot day^{-1}$) did not vary between filter systems and was dependant only on daily feed rate (Fig. 10b). Total ammonia production in all systems, except the fluidized bed (FB), increased linearly with daily feed (F=214.95, df=72, P<0.0000). Therefore at 7°C and using a 52% crude protein diet, the total amount of ammonia produced per day by Arctic charr can be predicted by:

(4) Total Ammonia ($g \cdot day^{-1}$) = 46.58 Feed (kg) - 8.68

Total ammonia produced in the FB did increase with feed levels, but not significantly (F=3.88, df=16, P=0.1436) (Fig. 10b). The lack of significance may be due to the variability of operating conditions occurring within this system.

Ammonia removal

As mentioned previously, the amount of ammonia removed by the biofilters depended on influent ammonia levels (Fig. 5). Influent ammonia levels in turn depend on daily feed (Fig. 10a), therefore we can develop a relationship for ammonia removal with increasing daily feed for each filtration system (Fig. 11a). The amount of ammonia removed ($g{\cdot}m^{-2}$ $SA{\cdot}day^{-1}$), increased linearly with increasing feed for the gravel filters (LGF,SGF) and the trickle filter (TF);

(5) Ammonia Removed ($g{\cdot}m^{-2}{\cdot}day^{-1}$) = a + b Feed (kg)

	df	F	Prob>F	SA	b	a
LGF	27	86.40	0.0000	328	0.11	-0.02
SGF	21	27.33	0.0000	118	0.25	-0.01
TF	22	7.09	0.0146	80	0.58	-0.02
FB	17	0.17	0.6831	100	-0.01	0.17

For the LGF, SGF and TF the rate of ammonia removal (b) depends on the amount of media surface area present within the filter (Fig. 11a). If we compare these rates of removal (SLOPE) to surface area, we find the following relationship;

(6) SLOPE = 0.57 + 0.0014 Media Surface Area

The greater the media surface area present within a filter, the lower the influent ammonia levels will be and the slower the rate at which ammonia is removed with increasing feed.

The previous equation (6) can be used to estimate SLOPE (B) values (rate of ammonia removal) for a range of filter sizes (118-328 m^2 SA). These estimated rates of removal can then be inserted into a standardized ammonia removal/daily feed equation derived from (5);

(7) Expected Removal ($g{\cdot}m^{-2}$ $SA{\cdot}day^{-1}$) = B Feed (kg)

With these equations we can predict the expected mean ammonia removal rates for a particular feed level and media surface area.

e.g. media surface area = 200 m^2
daily feed = 1.1 kg

SLOPE = 0.57 - 0.0014 Media Surface Area
= 0.57 - 0.0014 (200)
SLOPE = 0.29 = B

Expected Ammonia Removal ($g{\cdot}m^{-2}{\cdot}day^{-1}$)= B Feed (kg)
= 0.29 (1.1)
Expected Ammonia Removal = 0.32 $g{\cdot}m^{-2}$ $SA{\cdot}day^{-1}$

As the ammonia removal rates varied with feeding rate and media surface area, the total amount of ammonia removed per day ($g{\cdot}day^{-1}$) depended only on daily feed (Fig. 11b). The total ammonia removed in all systems, except the fluidized bed (FB), increased linearly with daily feed (F=150.31, df=72, P<0.0000). The small gravel filter (SGF) had approximately one third the media surface area as the large gravel filter (118 vs 328 m^2 SA), however it was able to remove the same amount of ammonia on a daily basis, as the LGF (Fig. 11b). Therefore at 7°C and using a 52% crude protein diet, the total amount of ammonia removed per day by these filtration systems can be predicted by;

(8) Ammonia Removed ($g{\cdot}d^{-1}$)= 34.79 Feed (kg) - 6.68

DISCUSSION

Of the four filtration systems tested, the large gravel filter (LGF) maintained the best overall water quality. In comparison the small gravel filter (SGF), which received effluent from the same fish density, had higher mean ammonia levels. These levels did not however, seem unacceptable for fish production as indicated by the low mortality and growth rate similar to the LGF. The plastic media trickle filter (TF) had ammonia levels similar to SGF, even though this system had a lower final fish density (110 $kg{\cdot}m^{-3}$ versus 160 $kg{\cdot}m^{-3}$). The fluidized bed system was not able to maintain ammonia levels below 700 $\mu g{\cdot}L^{-1}$, as did the other systems. These higher levels were unacceptable due to the large mortality of the rainbow trout in this system. These results support Larmoyeux and Piper (1973) findings that the growth of rainbow trout was not effected for ammonia levels up to 1000 $\mu g{\cdot}L^{-1}$ when sufficient oxygen was present, but that a decline in growth did occur with low oxygen and ammonia levels exceeding 500 $\mu g{\cdot}L^{-1}$. Of all the filtration systems, the fluidized bed was the only system which had difficulty in maintaining oxygen levels greater than 600 $\mu g{\cdot}L^{-1}$.

Under conditions of low fish density (37-100 $kg{\cdot}m^{-3}$) ammonia levels in LGF varied with the backwash schedule. For several days after each backwash, ammonia levels would reach values 2-5 times that occurring before the backwash. This reduction in ammonia removal efficiency may be caused by too vigorous a backwash. As the highest concentration of nitrifiers occur in the portion of the biofilm which is exposed to the greatest concentration of ammonia and oxygen, i.e. the surface of the biofilm (Harremoes 1982), it is possible that a vigorous backwash may expel a significant portion of the nitrifying community. The nitrification bacteria are typically slow growing bacteria (Haug and McCarty 1972; Harremoes 1982), who's growth rate is temperature related and where optimal growth occurs between 25-30°C (Knowles et al. 1965). Therefore at 7°C, it may take several days for the nitrifying population to grow to the point where they can effectively remove the influent ammonia.

Another possibility may be that the debris which accumulates within the filter bed between backwashes is a significant source of secondary ammonia (Liao and Mayo 1974). When the filter is backwashed the debris is removed and it takes several days for it to accumulate again. At these low fish densities, a single pass of water through the filter bed effectively removed almost all the ammonia (mean effluent=22 NH3-N $\mu g \cdot L^{-1}$). Therefore the ammonia load entering the filter bed after a backwash (with no secondary ammonia), would be relatively small. As ammonia removal is highly dependent on influent ammonia levels (Liao and Mayo 1974), the low ammonia levels occurring immediately after a backwash may be causing a slow down in the metabolic rate of the nitrifying bacteria, such that over several days ammonia begins to accumulate within the system. As fish density and ammonia load increased beyond these initial densities, the magnitude of the cycling gradually declined until no cycling was apparent during the final fish load.

Within the small gravel filter (SGF), no cycling of ammonia levels was apparent during any stage. Any cycling within the initial loading phase may have been obscured by the development of the nitrifying community. Experimentation of this system began with clean filter material, unlike the LGF which already possessed a functioning nitrification community. Once established (as during the second loading phase), the small gravel filter was not as effective as the LGF in removing all the ammonia in a single pass. Mean effluent levels in SGF were 115 $\mu g \cdot L^{-1}$, which may have been sufficient to prevent a decline in ammonia load and subsequent removal rates, thereby preventing ammonia cycling. As both the LGF and SGF were backwashed in a similar fashion, the cycling which occurred in LGF alone was most likely due to some other operational characteristic, such as influent ammonia levels.

During the final loading phase in the small gravel filter (SGF) ammonia levels exceeding 900 $\mu g \cdot L^{-1}$ did occur. However, these higher levels were alleviated by the mechanical changes made to the filter bed. The mat of debris which developed on the filter bed is high in organic matter and supports the growth of heterotrophic bacteria (Liao and Mayo 1974). This heterotrophic community has a high oxygen demand and grows rapidly. As a result, the nitrifying bacteria are not able to compete effectively against this community (Kruner and Rosenthal 1987), which in turn results in declining ammonia removal efficiencies and higher ammonia levels (Prakasam and Loehr 1972; Torpey et al. 1971; Weng and Molof 1974). With the addition of the coarse gravel and spray bar into the filter of SGF, the development of this mat and its inhibitory effects were much reduced.

The trickle filter was designed to compare the ammonia removal abilities of two types of plastic media. The Tripacks and Ballast rings differ in two fundamental ways; 1) physical characteristics (e.g. shape, packing ratio, etc.) and 2) specific surface area. The differences in physical characteristics may influence such things as flow dynamics and biofilm development, which in turn may possibly influence ammonia removal. The fact that there was no difference in the amount of ammonia removed per square metre of surface area between media types, would indicate that the physical differences are not great enough to influence removal under the conditions tested here.

If we assume that the total amount of ammonia removed is directly proportional to surface area, then on a volume basis, the Tripacks should be able to remove 33% more ammonia than the Ballast rings, as they have 33% more specific surface area ($m^2 \cdot m^{-3}$). The fact that the Tripacks could only remove 15% more ammonia may be due to operational conditions rather than media characteristics. Due to the differences in media volumes (Ballast 0.22 m^3, Tripack 0.12 m^3), retention time in the Tripack tower was half that in the Ballast tower. As ammonia removal is dependent on retention time (Liao and Mayo 1974), this difference may have reduced the removal effectiveness of the Tripacks.

Possibly of greater importance, may be the simple difference in depth of the filter media. The depth of Tripacks was 40 cm, compared to 75 cm for the Ballast rings. In general the upper half of a biofilter removes more organic matter than the lower half, with the majority of nitrification occurring within the deeper zones of the filter (Kruner and Rosenthal 1983; Balakrishnan and Eckenfelder 1969). Therefore within a short filter, as the Tripack tower, the development of a sufficient nitrification community may be severely limited, thereby limiting the ammonia removal potential.

The only modification of the fluidized bed which produced any change in water quality was the change from compressed to blown air. The increased flow rate which resulted, produced a significant decline in influent ammonia levels. As other investigators have found (LaMotta 1976), an increase in fluid velocity can have a positive effect on the rate of substrate uptake.

It is generally known that ammonia removal depends on initial ammonia loads, where removal increases as ammonia load increases (Liao and Mayo 1974). This phenomenon was observed only within the two gravel filters. Within the trickle filter and fluidized bed the ammonia removal rates were similar at all loads. Ammonia removal can only increase to a maximum level. This level being determined by oxygen levels (Bovendeur et al. 1987), organic load (Liao and Mayo 1974), or can be reaction rate limited (Harremoes 1987). The steady removal rates within the trickle filter and fluidized bed would indicate that removal in these systems had reached this maximum level. Due to the relatively small amount of media surface area in both filters and the large fish loads supported by them, it may be that these filters are rate limited and can remove no more ammonia.

According to Hess (1981) there are three areas in the filter design problem: 1) estimating ammonia production, 2) allowing for effects of the reuse systems and its multiple passes on ammonia concentration and 3) sizing of the filter bed. As other studies have found (Willoughby 1968; Speece 1973), the ammonia produced within these systems was directly related to feeding level. The amount of ammonia produced within these filtration systems (38 $g \cdot kg^{-1}$ feed) was higher than other published results (26 $g \cdot kg^{-1}$ feed at 10°C, Speece 1973), however there was no indication of the protein content of the food used to determine this value. Not only can we predict the total daily ammonia production, but influent ammonia levels ($\mu g \cdot L^{-1}$) for any size of filter (118-328 m^2 SA), can also be determined for any particular feeding level. These values can be useful in determining the carrying capacity of a particular filter, or be used to set water quality standards for experimental tanks. The second part of Hess's problem of allowing for system effects has been taken into account in the development of the ammonia production and removal relationships.

It is generally known that ammonia removal rates increase with ammonia load (Bovendeur et al. 1987), and we have seen that this rate of increase depends on filter size. The mean removal rate for the trickle filter (TF) (0.45 g NH_3-$N \cdot m^{-2}$ $SA \cdot day^{-1}$) was the highest obtained for all filters. TF has approximately one-quarter the media surface area of the large gravel filter (LGF), and in turn almost five times the rate of ammonia removal (LGF 0.07 g NH_3-$N \cdot m^{-2}$ $SA \cdot day^{-1}$). TF also had higher mean ammonia levels which support the hypothesis that the magnitude of the intrinsic substrate uptake rate increases as influent substrate concentration increases (LaMotta 1976). The rates of removal obtained in this study are similar to other published rates for rainbow trout at 15°C, of 0.25 g NH_3-$N \cdot m^{-2} \cdot day^{-1}$ (Bovendeur et al. 1987)

On a daily basis, the total ammonia removal capabilities of all filtration systems except the fluidized bed, are the same at any particular feeding level. Even though SGF has one-third the media surface of LGF, SGF can remove the same amount of ammonia per day. This indicates that the nitrifying bacteria have a broad range of adaptability, ie given the same ammonia load but differing amounts of media surface area, they are capable of removing the same amount of ammonia. According to Hess (1981) this "normal vigour level of nitrifying bacteria" is the key to the sizing procedure, as this is the one filter effectiveness parameter that carries the same value from one filter to another, independently of flow rate, load, filter dimensions, etc. Indeed if this relationship did not hold for the filtration systems investigated here, the sizing procedure developed would not be useful, except to size filters with the same operation characteristic from which the relationship was derived.

The sizing procedure is summarized as follows;

1) determine the volume of the rearing unit to be used
2) determine the final fish density that the rearing unit will contain
3) determine the feeding rate ($kg \cdot day^{-1}$) that this final density will receive
4) determine the maximum acceptable ammonia level ($\mu g \cdot L^{-1}$) that this final density should be exposed to
5) place this influent ammonia level and feed level (step 3) into the following formula to determine b

$$\underline{b} = \frac{\text{LN Influent N 3-N Level } (\mu g \cdot L^{-1})}{\text{Daily Feed (kg)}}$$

6) place the calculated b into the following equation to determine the surface area (SA) required

$$\text{Media Surface Area } (m^2 \text{ SA}) = \frac{\underline{b} - 5.59}{0.007}$$

7) from this value of surface area required determine the volume of filter substrate that would be required to provide this surface area.

It must be remembered that this sizing procedure was developed for systems at 7°C and with a 52% crude protein diet. As ammonia production (Speece 1973) and ammonia removal (Knowles et al. 1965) are temperature dependent, further experimentation would be required to develop a procedure at other temperatures.

SUMMARY

Both gravel filters were effective at maintaining acceptable ammonia levels at high fish densities. In terms of maintenance, the small gravel filter (SGF) required less time to backwash than the large gravel filter (LGF). Economically SGF is superior, as it is located directly beneath the rearing unit, optimizing floor space. In addition, much less substrate is required by the smaller filter.

The fluidized bed was not effective at maintaining acceptable ammonia levels at high fish densities. This systems may be better suited for maintaining broodstock tanks, which contain much lower fish densities. The trickle filter may be especially suited for broodstock, due to the very low maintenance required. Basically only one backwash per month was required, as compared to the fluidized bed which required two per week. A minimum media depth of 80 cm should be used for the plastic media trickle filter. Since the Ballast rings work equally well as the Tripacks, at only a fraction of the purchase price, the Ballast rings should be preferred.

Overall, the fluidized bed had several design problems which hindered its effectiveness at high fish densities. The division of flow, which returns 50% of the airlifted water back to the rearing unit without being filtered, was designed to provide sufficient aeration for the rearing unit. However, as most airlift pumps are normally driven by blown air, there is usually a surplus of air which could be used to aerate the fish tank directly. The entire flow should be directed through the filter to maximize ammonia removal. The position of the filter inflow and outflow at the same end of the system does not promote flow through conditions which utilize the entire filter bed. The backwash system was not sufficient to maintain the filter free of debris over time.

The sizing procedure should only be considered preliminary as it was developed from a limited number of systems. The equations developed here should only be applied to other systems with caution. The methodology of developing these relationships however can easily be applied to other systems. Much more work with systems of different designs, sizes and temperature ranges is required before this sizing procedure can be applied with confidence.

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REFERENCES

BALAKRISHNAN, S., and W. W. ECKENFELDER. 1969. Nitrogen relationships in biological treatment processes. I. Nitrification in the activated sludge process. Water Res. 3: 73-81.

BOVENDEUR, J., E. H. EDING, and A. M. HENKEN. 1987. Design and performance of a water recirculation system for high-density culture of the African catfish, Clarias gariepinus. Aquaculture 63: 329-353.

HAUG, R. T., and P. L. McCARTY. 1972. Nitrification with submerged filters. J. Water Pollut. Control Fed. 44: 2086-2102.

HARREMOES, P. 1982. Criteria for nitrification in fixed film reactors. Water Sci. Technol. 14: 167-187.

HARREMOES, P. 1978. Biofilm kinetics, p.71 In R.Mitchell (ed.) Water pollution microbiology Vol. 2. John Wiley, Toronto Ontario.

HESS, W. J. 1981. Performance ratings for submerged nitrification biofilters, development of a design calculation procedure. Bio-Engineering Symposium for Fish Culture. p. 63-70.

KNOWLES, G., A. L. DOWNING, and M. J. BARRETT. 1965. Determination of kinetic constants for nitrifying bacteria in mixed culture, with the aid of an electronic computer. J. Gen. Microbiol. 38: 263-278.

KRAUL, S., J. SZYPER, and B. BURKE. 1985. Practical formula for computing water exchange rates. Prog. Fish-Cult. 47: 69-70.

KRUNER, G., and H. ROSENTHAL. 1983. Efficiency of nitrification in trickling filters using different substrates. Aquacult. Eng. 2: 49-67.

KRUNER, G., and H. ROSENTHAL. 1987. Circadian periodicity of biological oxidation under three different operational conditions. Aquacult. Eng. 6: 79-96.

LaMOTTA, E. J. 1976. Kinetics of growth and substrate uptake in a biological film system. Appl. Environ. Microbiol. 31: 286-293.

LARMOYEUX, J. D., and R. G. PIPER. 1973. Effects of water reuse on rainbow trout in hatcheries. Prog. Fish-Cult. 35: 2-8.

LIAO, P. B., and R. D. MAYO. 1972. Salmonid hatchery water reuse systems. Aquaculture 1: 317-335.

LIAO, P. B., and R. D. MAYO. 1974. Intensified fish culture combining water reconditioning with pollution abatement. Aquaculture 3: 61-85.

LEITRITZ, E. 1980. Trout and salmon culture, hatchery methods. Calif. Fish Bull. 161: 64 p.

PRAKASAM, T. B. S., and R. C. LOEHR. 1972. Microbial nitrification and denitrification in concentrated wastes. Water Res. 6: 859-869.

SPEECE, R. E. 1973. Trout metabolism characteristics and therational design of nitrification facilities for water reuse in hatcheries. Trans. Am. Fish. Soc. 102: 323-334.

STAINTON, M. P., M. J. CAPEL, and F. A. J. ARMSTRONG. 1977. The chemical analysis of freshwater. Can. Fish. Mar. Serv. Misc. Spec. Publ. 25, 2nd ed.: 180 p.

TORPEY, W. N., H. HEUKELEKIAN, A. J. KOPLOVSKY, and R. EPSTEIN. 1971. Rotating disks with biological growths prepare wastewater for disposal or reuse. J. Water Pollut. Control Fed. 43: 2181

WENG, C., and A. H. MOLOF. 1974. Nitrification in the biological fixed film rotating disk system. J. Water Pollut. Control Fed. 46: 1674-1685.

WILLOUGHBY, H. 1968. A method for calculating carrying capacities of hatchery troughs and ponds. Prog. Fish-Cult. 30: 173-174.

Table 1. Operational data and characterisitics for the filtration systems and filter media.

Operational Data	Gravel Filter (LGF)	(SGF)	Trickle Filter (TF) Tripack	Ballast	Fluidized Bed (FB)
Filter					
Total Volume (m^3)	2.75	0.93	0.12	0.22	0.23
Water Volume (m^3)	1.70	0.55	-----	-----	0.13
Media Volume (m^3)	1.75	0.75	0.12	0.22	0.10
Filter Surface (m^2)	2.13	1.53	0.30	0.30	0.41
Flow Rate ($L \cdot min^{-1}$)	96	84	48	48	26
Make up ($L \cdot min^{-1}$)	12	20	8	8	21
Retention Time (min)	17.7	6.5	2.2	4.1	11.0
Hydraulic Load ($m^3 \cdot m^{-2} \cdot day^{-1}$)	64.9	79.1	230.4	230.4	91.3
Media					
Diameter (cm)	2.0	2.0	2.5	2.5	0.5
Specific Surface Area ($m^2 \cdot m^{-3}$)	203	203	283	212	1000
Surface Area Present (m^2)	328.3	117.8	33.4	46.6	100
Void Space (%)	40	40	91	90	36
Pieces/litre	480	480	87	48	17000

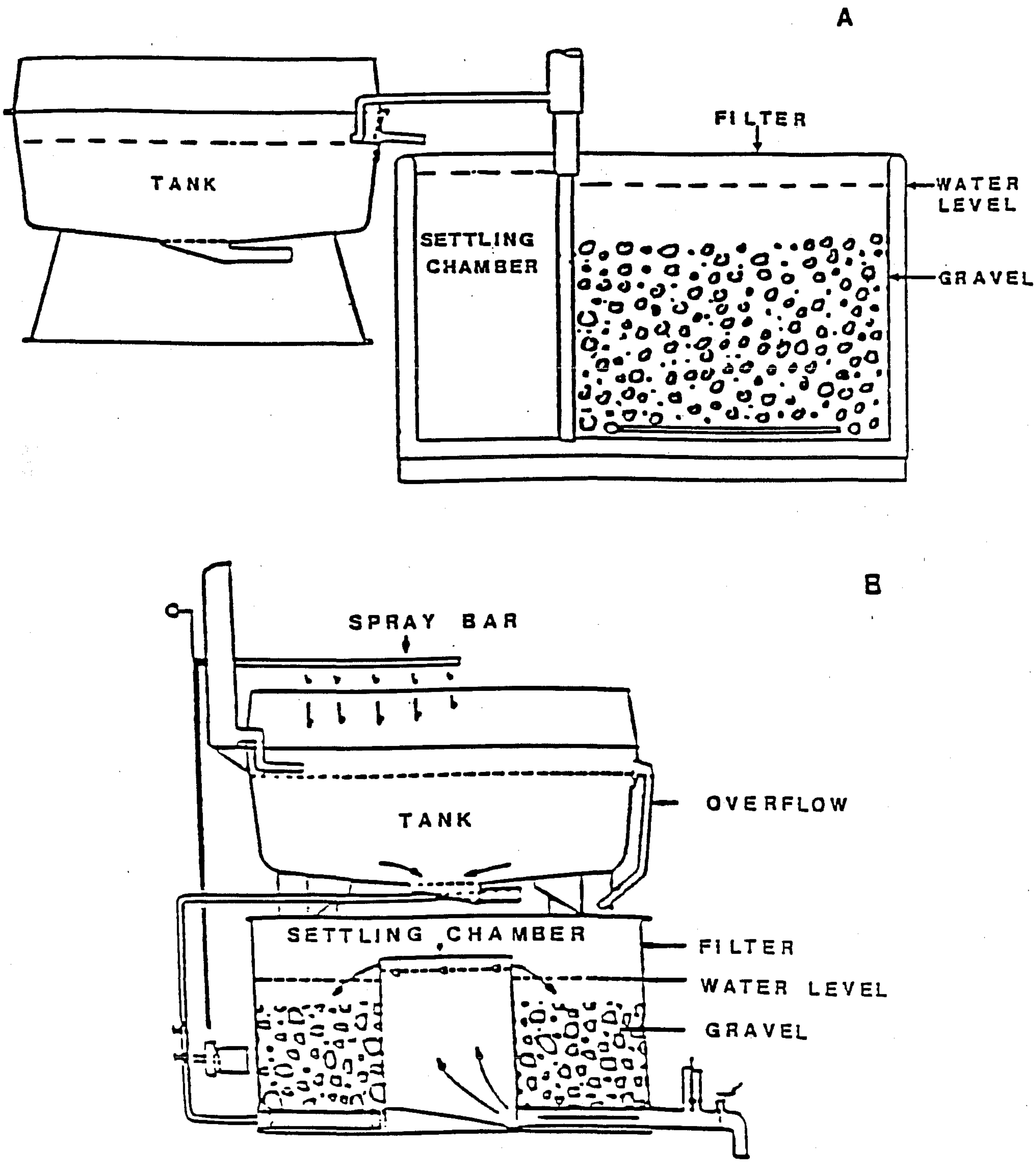


Figure 1. Schematic diagram of the large gravel filter (LGF) (A) and the small gravel filter (SGF) (B).

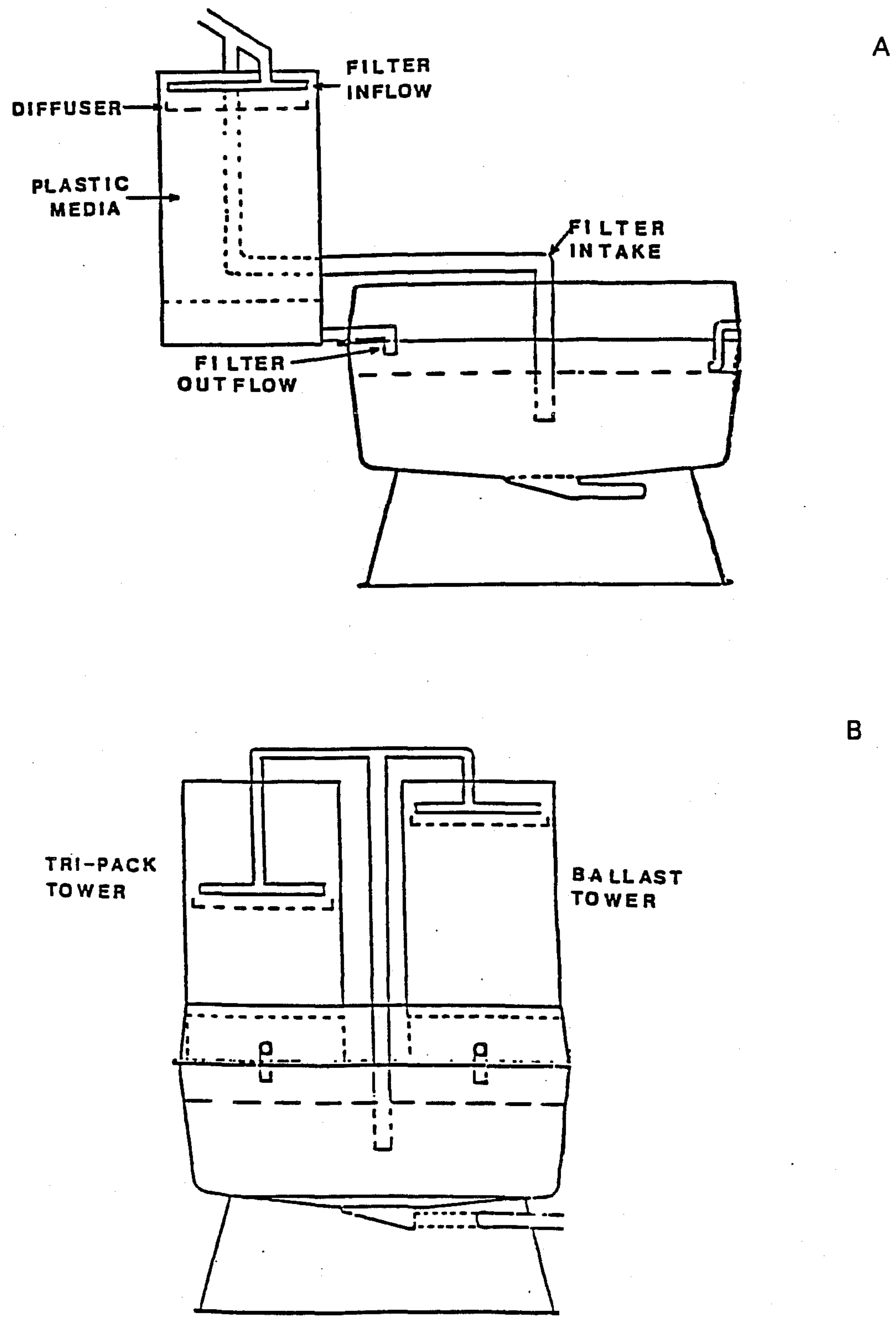
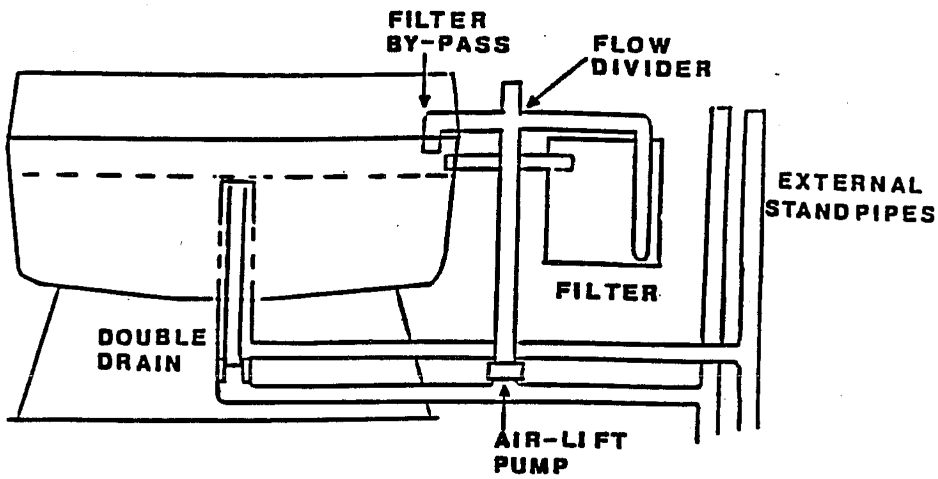


Figure 2. Schematic diagram of the plastic media trickle filter (TF). A=side view. B=front view.

A



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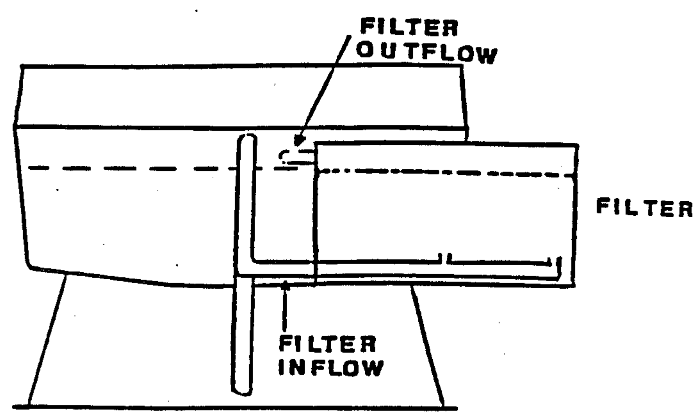


Figure 3. Schematic diagram of the fluidized bed (FB). A=side view. B=front view, external standpipes omitted.

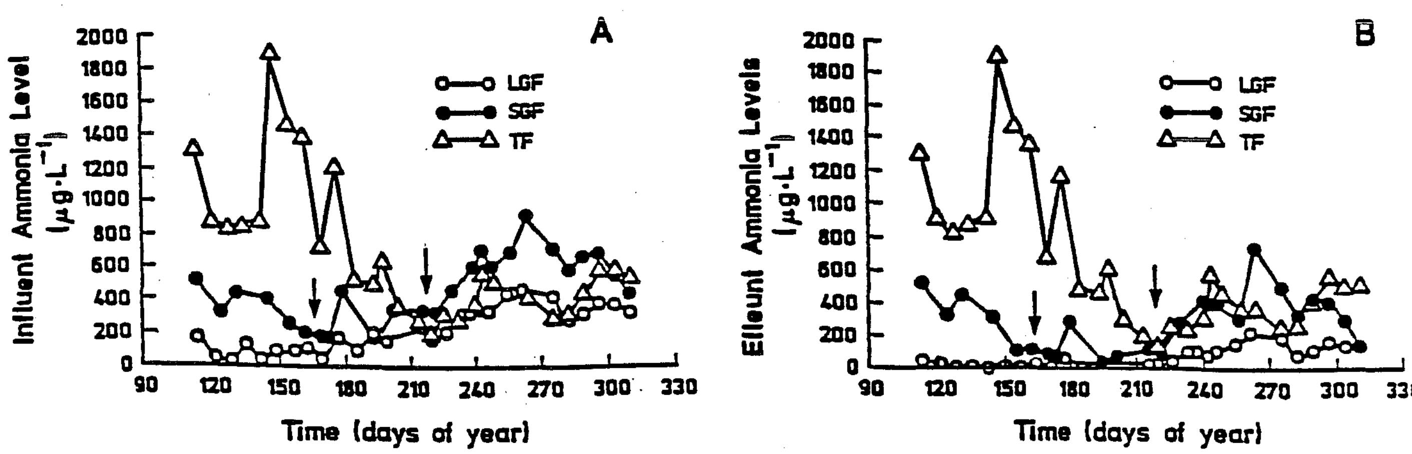


Figure 4. Influent (A) and effluent (B) ammonia levels for the large gravel filter (LGF), small gravel filter (SGF) and the trickle filter (TF). Arrows indicate time of increased fish loading.

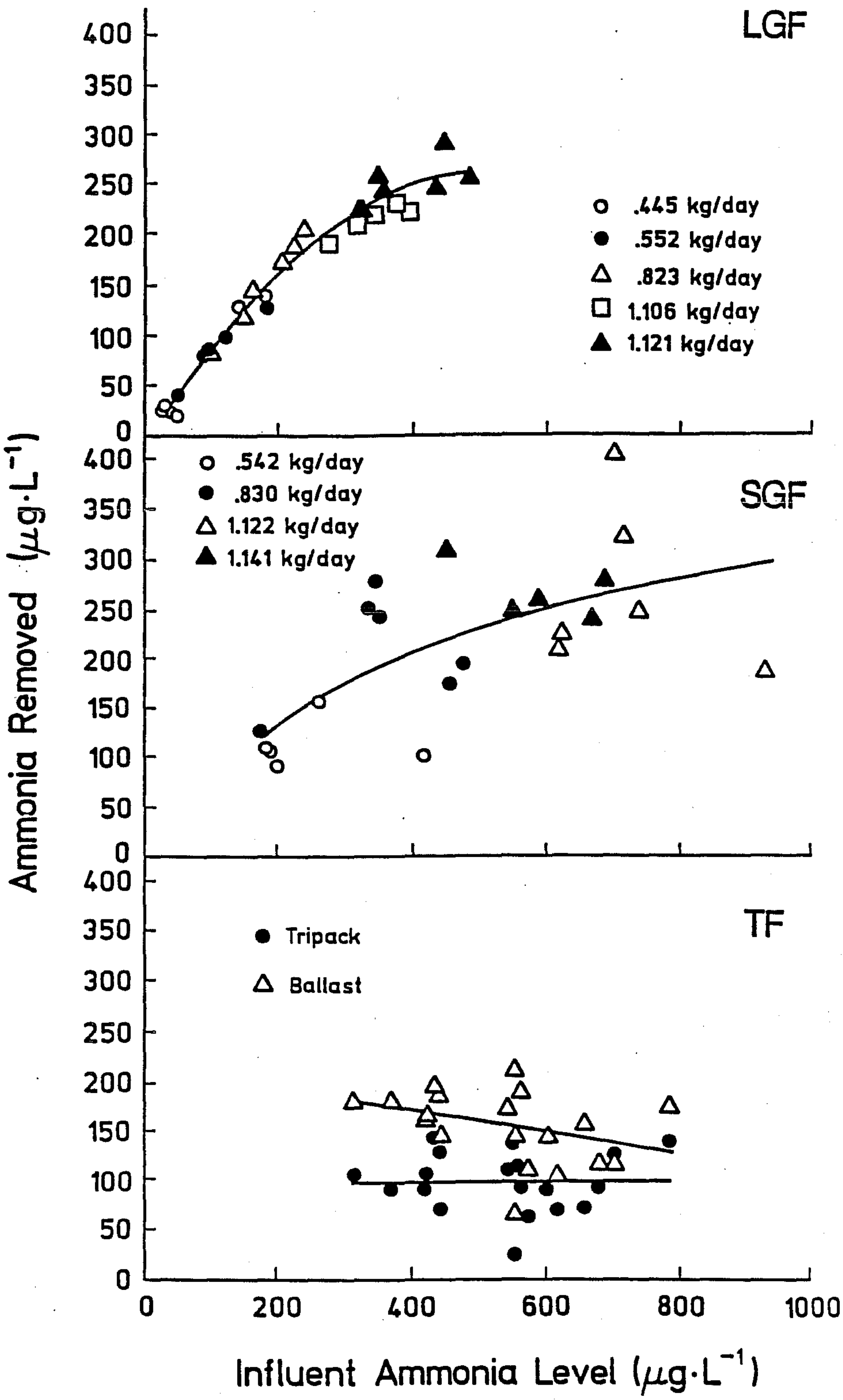


Figure 5. The amount of ammonia removed per litre with influent ammonia levels, at various feeding rates for the large gravel filter (LGF), small gravel filter (SGF) and the trickle filter (TF).

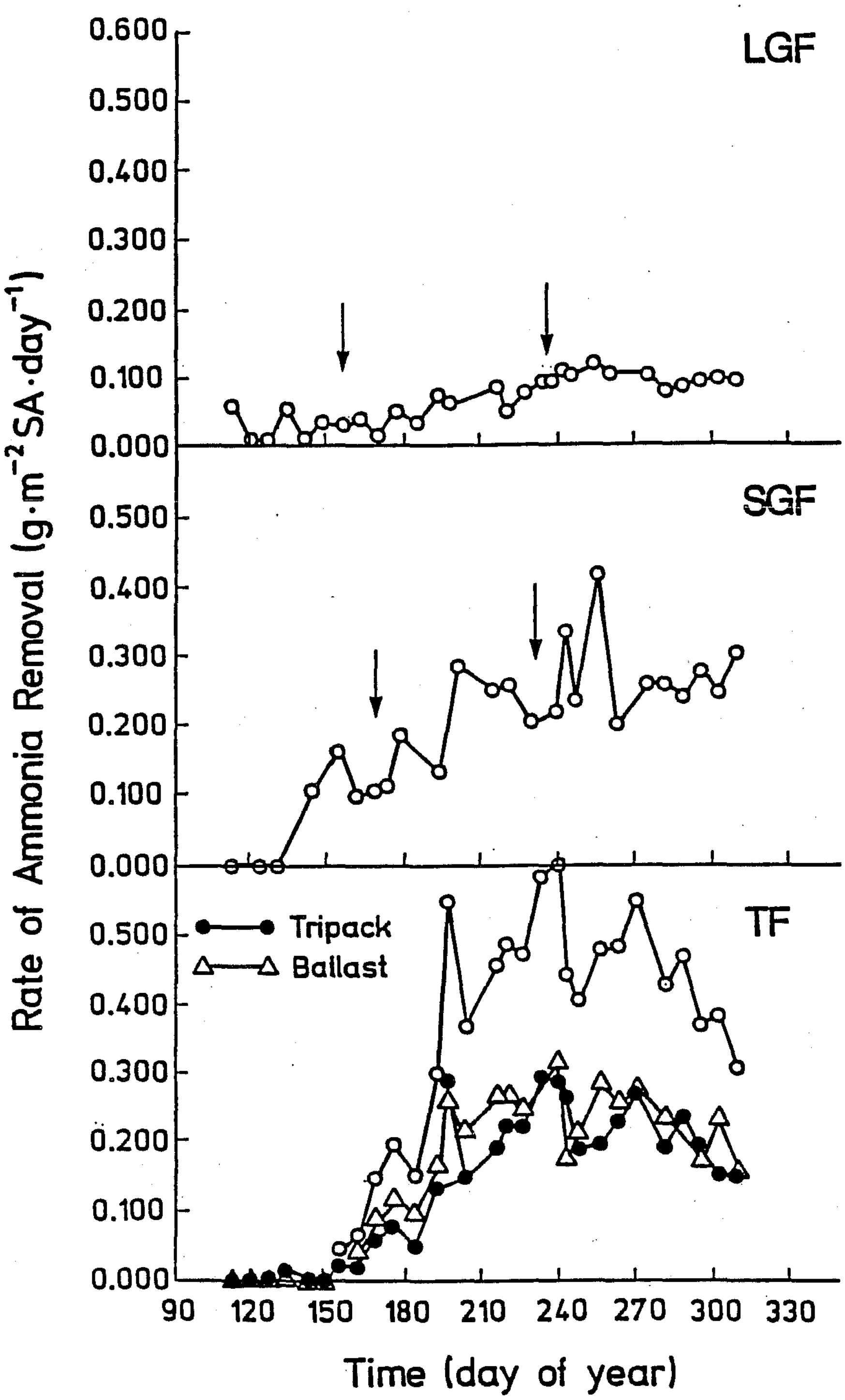


Figure 6. The rate of ammonia removal per square metre of media surface area for the large gravel filter (LGF), small gravel filter (SGF) and the trickle filter (TF). Arrows indicate time of increased fish loading.

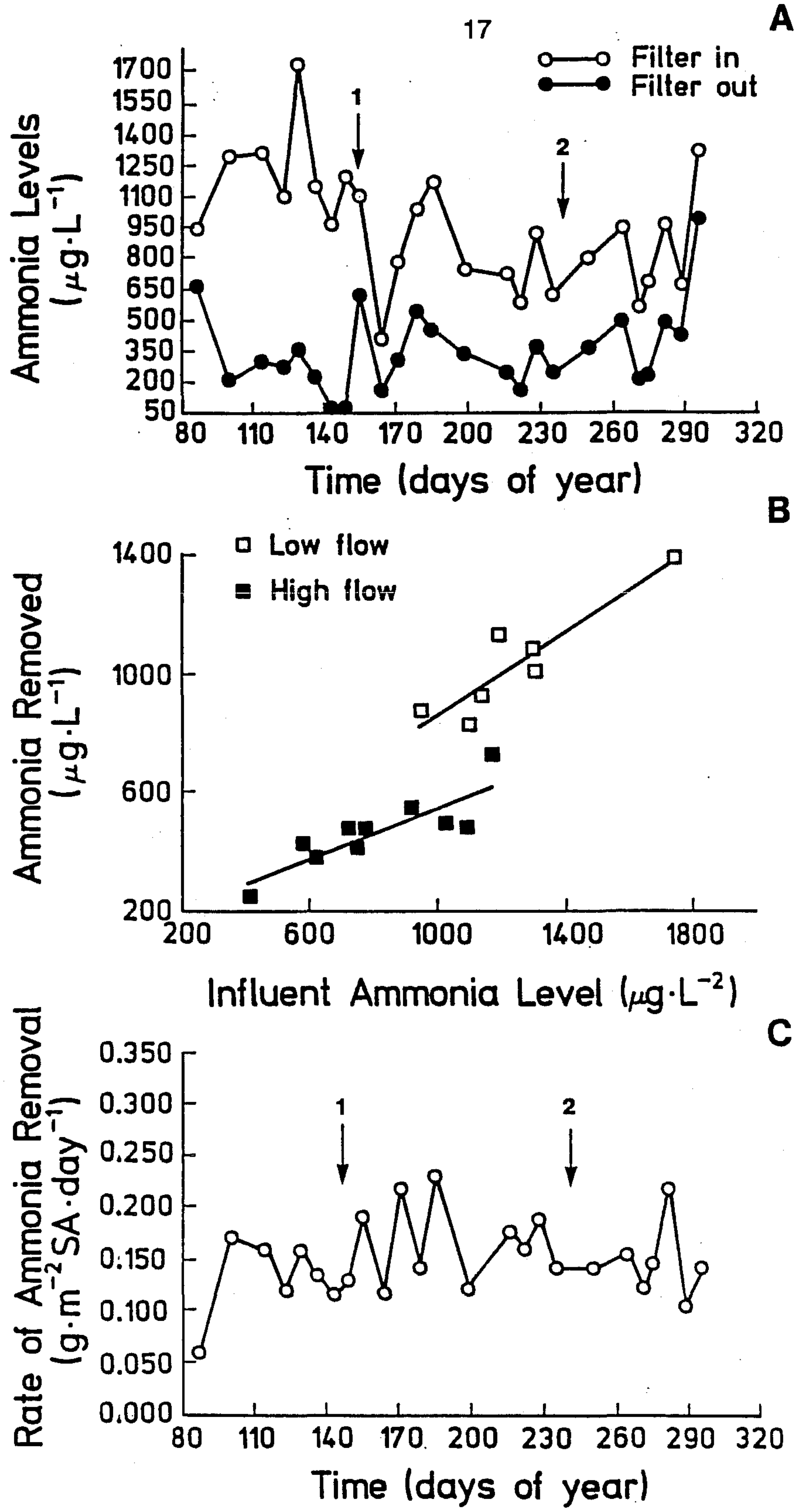


Figure 7. Influent and effluent ammonia levels for the fluidized bed (FB) (A). The amount of ammonia removed with influent ammonia levels under various flow rates (B). The rate of ammonia removal per square metre of media surface area (C). 1: indicates change from compressed to blown air. 2: indicates redesign of filter inflow.

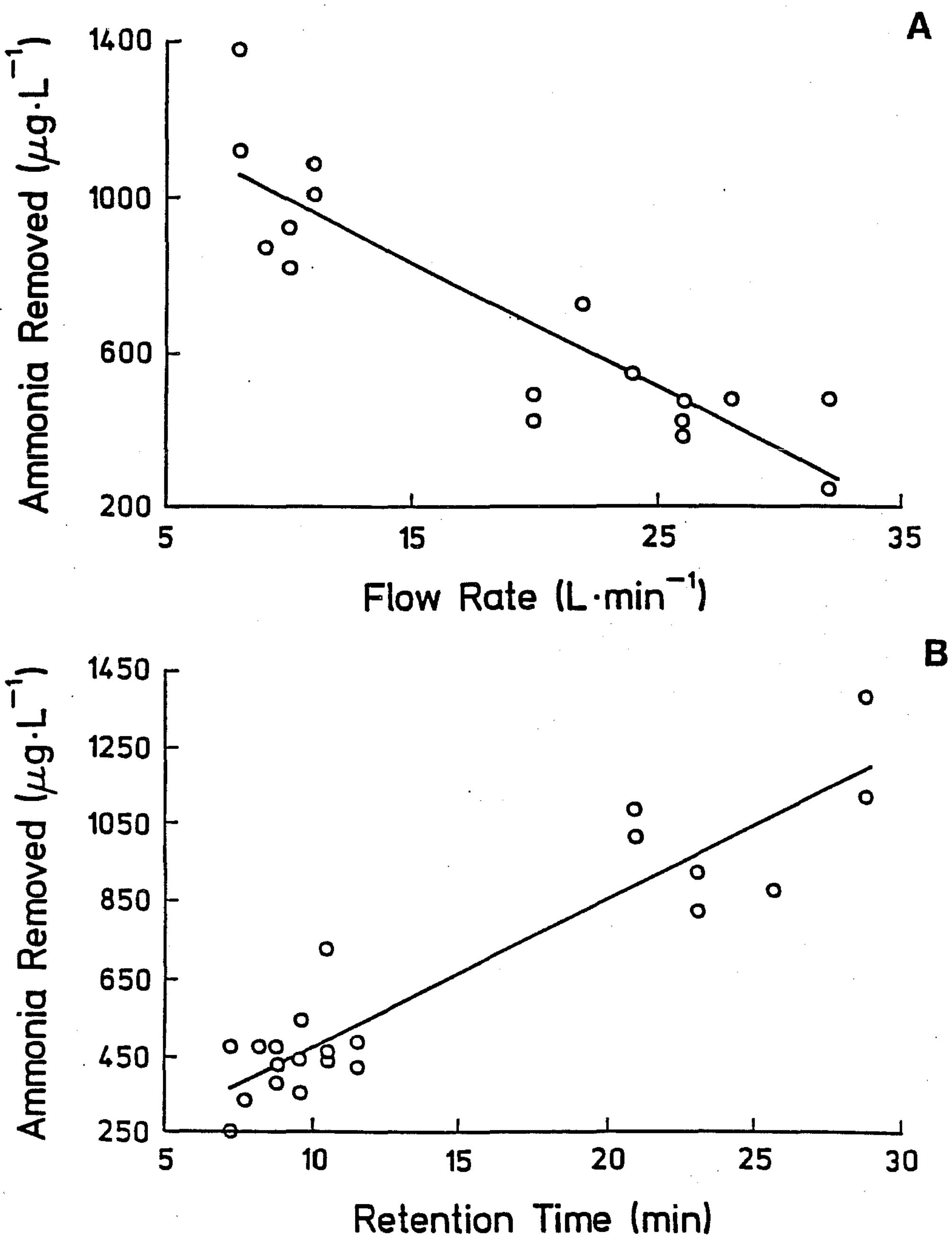


Figure 8. The amount of ammonia removed per litre with varying flow rates (A) and retention times (B) for the fluidized bed (FB).

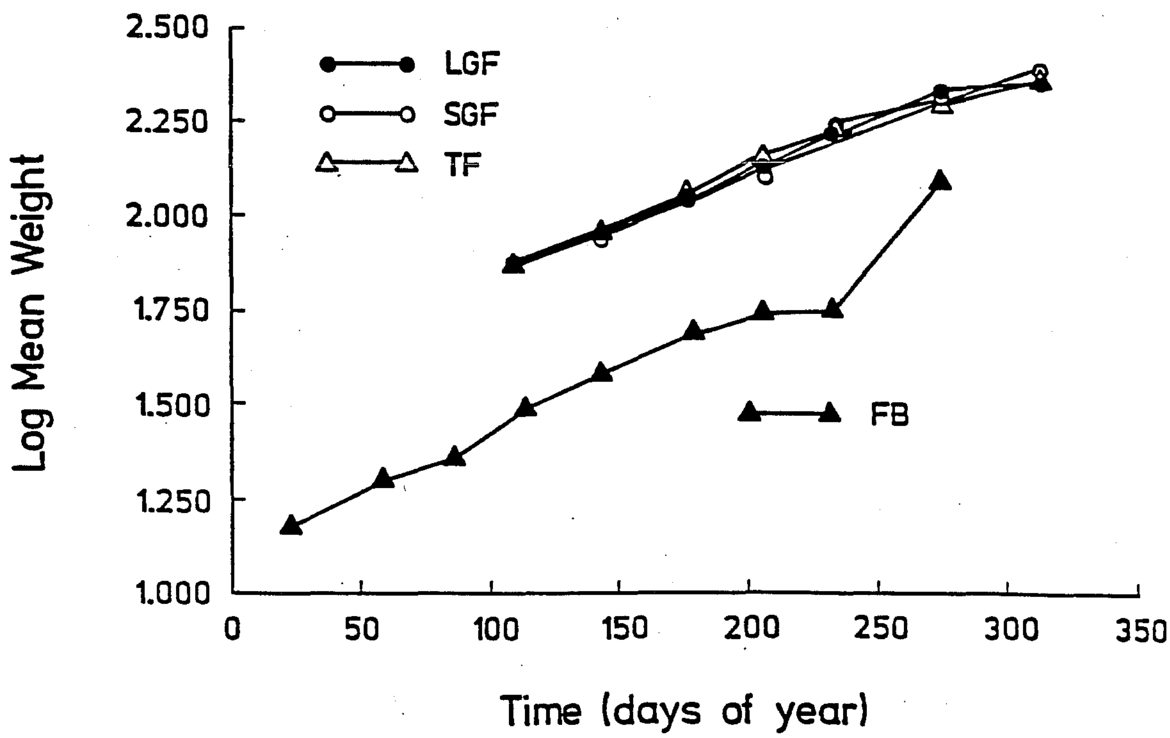
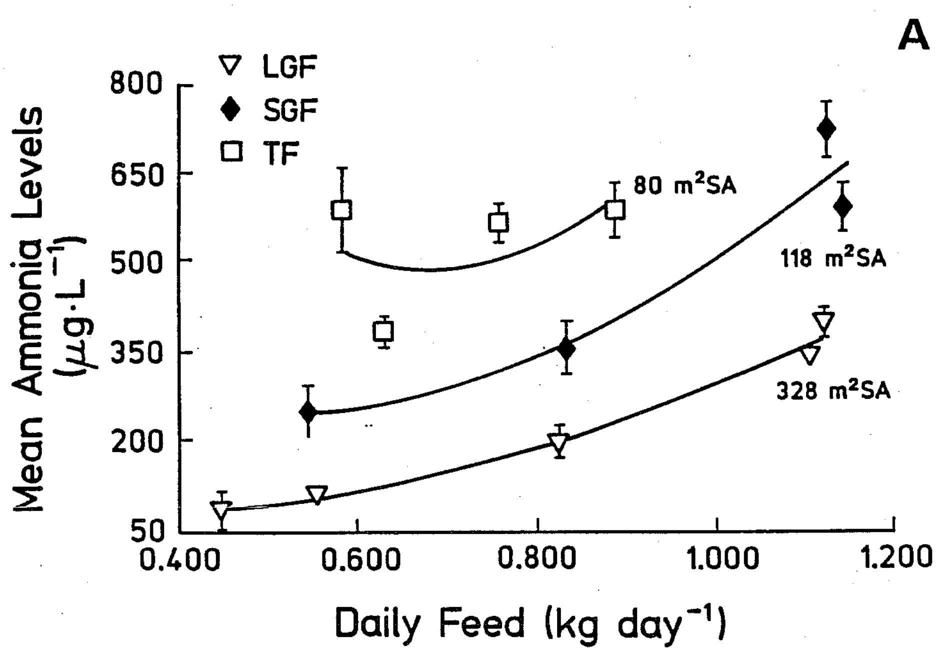


Figure 9. Specific growth rates for Arctic charr in the large gravel filter (LGF), small gravel filter (SGF) and the trickle filter (TF), and for rainbow trout in the fluidized bed (FB).



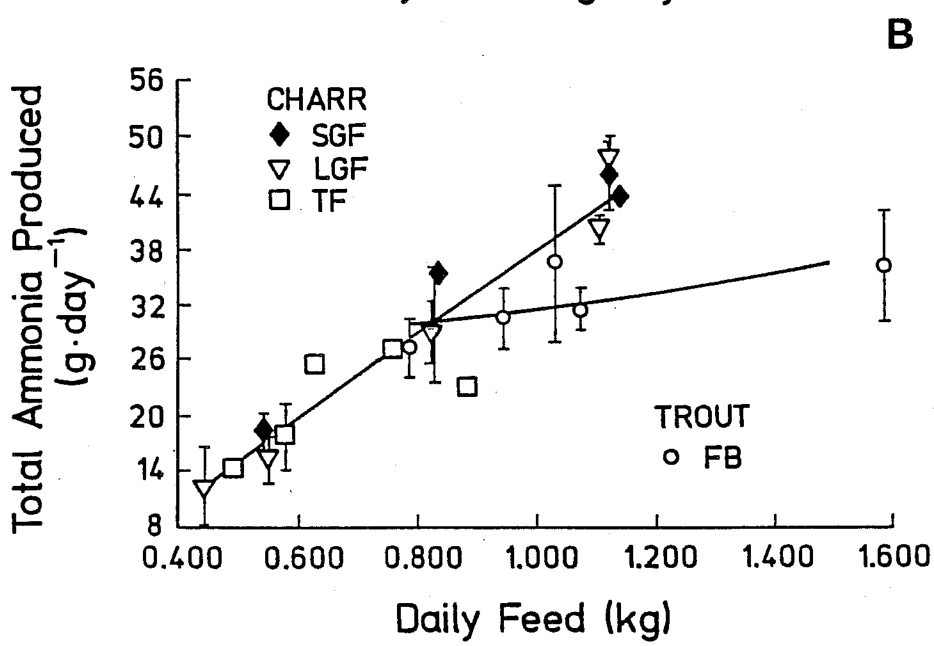


Figure 10. Mean influent ammonia levels with increasing daily feed for the gravel filters (LGF, SGF) and the trickle filter (TF) (A). Total daily ammonia production with increasing feed for all filtration systems (B).

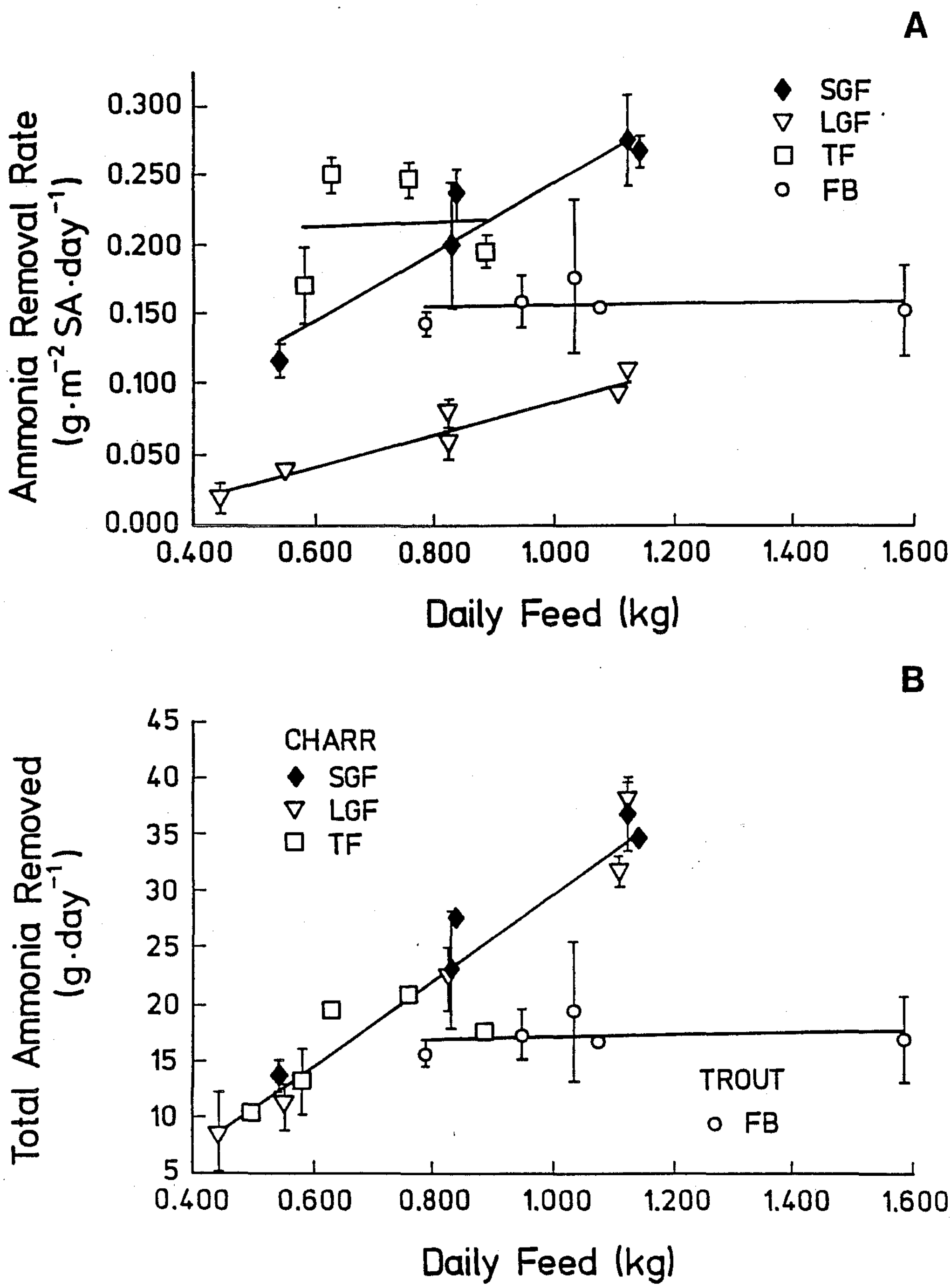


Figure 11. The amount of ammonia removed per square metre of media surface area (A) and total ammonia removed per day with increasing daily feed (B). LGF=large gravel filter, SGF=small gravel filter. TF=trickle filter. FB=fluidized bed.