Modeling the major limitations on nitrification in floating-bead filters[1]

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Abstract

A model was developed and calibrated to experimental data, to formulate a theoretical description of nitrification in bead filters. The model results were consistent with the literature, indicating that the inverse relationship between solids accumulation and nitrification is mediated by an oxygen limitation. This result was central to an explanation of why differing optimal backwash intervals in gently- and aggressively-washed filters are related to: (1) differences in harvest fraction, which fixes the relationship between backwash interval and interstitial solids concentration and (2) differences in biofilm retention, which controls the average biomass age thereby determining total biomass concentration.

Keywords: Aquaculture; Bead filters; Clarification; Model; Nitrification; Oxygen limitation

Nomenclature

μ_{mh}	Maximum heterotrophic specific growth-rate (d^{-1})
μ_{mn}	Maximum nitrifier specific growth-rate (d^{-1})
A_B	Biofilter TAN concentration (mg N/L)
A_T	Culture-tank TAN concentration (mg N/L)
B_B	Biofilter BOD concentration (mg BOD/L)
B_R	Biofilm-retention factor (unitless)
C_A	Apparent areal nitrification-rate (mg N/m^2-media/d)
E_S	Solids-excretion ratio (kg TSS/kg-feed)
f_b	Backwash frequency (d^{-1})
$1/f_b$	Backwash interval (d)
F_{LR}	Feed-loading rate (kg feed/m^3-media/d)
h_f	Harvest fraction (unitless)
$[H_S]$	Discreet solids harvest (mg TSS)
$[H_x]$	Discreet biomass harvest (mg VSS)
k_d	Specific endogenous decay-rate (d^{-1})
k_S	First-order specific solids decay-rate (d^{-1})
K_{SA}	TAN half-saturation constant (mg N/L)
K_{SB}	BOD half-saturation constant (mg BOD/L)
K_{SO}	Oxygen half-saturation constant (mg O_2/L)
n	Intrinsic porosity of the media (unitless)
O_B	Biofilter-oxygen concentration (mg O_2/L)
OCE_{AN}	Oxygen consumed in excess of apparent nitrification (mg O_2/d)

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OCF	Oxygen consumed in filtration (mg O_2/m^2-media/d)
OCN	Oxygen consumed for apparent nitrification (mg O_2/m^2-media/d)
O_T	Culture-tank oxygen concentration (mg O_2/L)
P_S	Primary solids (mg TSS)
Q_R	Recycle flow rate (L/min)
S_A	Media specific-surface area (m^2/m^3)
S_V	VSS:TSS ratio (unitless)
V_M	Volume of media (m^3)
X_H	Heterotrophic biomass (mg VSS)
X_N	Nitrifying biomass (mg VSS)
Y_N	Nitrifier yield (mg VSS/mg-N)

1. Introduction

Floating-bead filters (FBFs) have a demonstrated application, as part of the treatment required to maintain water quality in recirculating aquaculture systems (RASs). FBFs have been used solely to capture solids (delos Reyes and Lawson, 1996) and as “bio-clarifiers” that simultaneously perform clarification and biofiltration (Hargrove *et al.*, 1996). When bead filters are used as integrated bio-clarifiers they reduce the required number of system components. However, the unchecked accumulation of primary solids in the filter can depress nitrification through a cascade of interrelated mechanisms, collectively referred to as solids-loading effects. Those effects can be mitigated by backwashing, but this also removes slow-growing nitrifying bacteria. This paper discusses a model that was developed to describe the impact of solids accumulation and backwashing on nitrification in FBFs.

The first use of a FBF as a bio-clarifier in a RAS was at Dworshak National Fish Hatchery, where a pneumatically-washed filter was employed (Cooley, 1979). More recently, a hydraulically-washed filter was developed and tested at Louisiana State University (Wimberly, 1990). These filters delivered a relatively gentle wash, and nitrification increased with washing frequency. These studies suggested that nitrification in FBFs was limited only by solids. This belief held until subsequent research with a propeller-washed filter, which delivered a more-aggressive wash, revealed that nitrification can decline in response to more frequent washing (Chitta, 1993). This latter study indicated that a more-energetic wash can result in a biomass limitation at shorter backwash intervals (Golz *et al.*, 1996).

Most bead filters can be classified as belonging to a gently- or aggressively-washed regime. The reference to washing energy is only qualitative at present, but each regime exhibits a characteristic relationship between backwash interval and nitrification. This is clearly the result of the differing energy delivered by their washing mechanisms.

The gently-washed class includes the pneumatically- and hydraulically-washed filters discussed above, as well as the bubble-washed bead filter (BBF) (Sastry, 1996). The major limitation on this filter regime is solids accumulation. This is readily apparent because nitrification improves in response to more frequent backwashing. The relationship between backwash interval and nitrification appears to result from low solids- and biomass-removal rates. The small solids harvest equates to comparatively large solids concentrations at any given backwash interval. The inhibitory effects of the solids can, however, be mitigated by frequent washing, because the low biomass-loss rate provides for the existence of a sufficient population of nitrifiers at even the shortest backwash intervals.

Aggressively-washed filters, like the propeller-washed bead filter (PBF), characteristically achieve optimal nitrification at a single critical backwash interval (Chitta, 1993). These filters impart more energy to the bead bed during backwashing, resulting in larger harvest fractions and higher biofilm-removal rates (Golz, 1997). The magnitude of biofilm removal can result in a biomass limitation, which is manifest as diminished nitrification at shorter backwash intervals (Malone *et al*., 1993). The biomass limitation can be overcome by extending the backwash interval; and this is possible because the larger harvest-fraction yields lower solids concentrations at even relatively-long backwash intervals (Golz, 1997). The marked difference in optimal backwash intervals in gentle versus aggressive washing regimes established the need to develop a better description of the major limitations on nitrification in FBFs.

This paper discusses a theoretically-based model that was developed to describe dynamic biofiltration in a packed bed. To the extent of the search conducted by the authors, such a model did not exist in the literature. Therefore, the theory underlying the behavior of packed beds is discussed, and FBF behavior is explained in that larger context. The model results indicated that the inverse relationship between solids accumulation and nitrification in FBFs is mediated by an oxygen limitation. This result is central to explaining why differing optimal backwash intervals in gently- and aggressively-washed filters are related to: (1) differences in harvest fraction, which fixes the relationship between backwash interval and interstitial-solids concentration and (2) differences in biofilm retention, which controls the average biomass age thereby determining total biomass concentration.

2. Background

2.1 Filter configuration and operation

The gently- and aggressively-washed FBFs that are the subject of this study had similar physical configurations, employing 5 mm polyethylene-bead media (Chitta, 1993; Sastry, 1996). Their respective filtration modes were also similar: the beads form a packed bed, where solids are captured and attached and interstitially-suspended bacteria remove soluble contaminants from the recirculating water.

Backwashing is initiated to expel solids from the bed and consists of interrupting the normal filtration cycle and agitating the bed. The percentage of total solids released during a backwash is referred to as the harvest fraction, and it accounts for the removal of fecal matter and biomass. The removal of interstitial biomass cannot be controlled independently of the primary solids, because once the bed is expanded settling velocities dictate that fecal solids and biomass will be removed at similar rates (Chitta, 1993; Metcalf and Eddy, 1991). Research observations have indicated that the two filter regimes retain a different percentage of viable biofilm following a backwash (Chitta, 1993; Sastry, 1996). This is referred to as a difference in biofilm retention. However, the simple destruction of bacterial colonies, both suspended and attached, may be equally important (Golz, 1997).

Filter behavior clearly indicates that the differing biofilm-removal rates in the two filter regimes are attributable to their washing mechanism. The gently-washed BBF uses an influx of air to decrease the density of the water column in the filter (Sastry, 1996). This causes the bead bed to sink, and the solids are released as the beads gently swirl through a washing throat. The energy delivered during a wash is relatively constant, as the sum of the change in the bed's potential energy and the kinetic energy imparted to the beads. The aggressively-washed PBF employs a propeller turning at a shaft speed of 1750 RPM to expand the bed (Chitta, 1993; Malone *et al.*, 1993). The energy delivered is variable, because it is not only a function of shaft horsepower, which is fixed, but washing duration, which can be varied. Washing energy, which is obviously greater in the PBF, can be quantified for these two filters. However, the shear imparted to the beads has not been studied, and whether total energy or peak shear controls biofilm retention is not known.

2.2 The effects of solids accumulation on nitrification

When an FBF is operated under a low solids loading, or backwashed frequently, it will behave like a classical biofilm reactor. The exchange of soluble substrate between the recirculating water and the attached bacterial growth is relatively unimpeded, and under the usual conditions present in a RAS, the process will be total-ammonia nitrogen (TAN) limited (Malone *et al.*, 1993). However, when the solids loading is large or the backwash interval infrequent, nitrification can become inhibited when larger interstitial solids concentrations lead to: physical occlusion (Malone *et al.*, 1993); an increase in soluble contaminants (Metcalf and Eddy, 1991; Ning, 1995; Wang, 1995); a larger heterotrophic population (Manem and Rittmann, 1992; Zhang *et al.,* 1995); and the formation of macro-particles (Shammas, 1986). These factors are directly related to solids concentration. For a given system, the solids concentration is closely related to the length of time that the primary solids are held in the filter, i.e. the solids-residence time (SRT).

Physical occlusion is the most obvious effect of solids accumulation. It reduces filter flow and, thereby, mass-delivery rates (Sastry, 1996). In the systems used to calibrate the model discussed in this paper (Chitta, 1993; Sastry, 1996), the flow rates were sufficient to deliver both oxygen and TAN in the stoichiometric equivalents necessary to mineralize of all the excretion products (Golz *et al.,* 1996). This held for all backwash intervals, even those beyond the point where nitrification declined. Similar observations have been reported in studies based upon rotating biological contactors and trickling filters (Bovendeur *et al.*, 1990; Figueroa and Silverstein, 1992). In a study conducted by Hargrove *et al.* (1996) on experimental-scale FBFs, no significant correlation existed between TAN-mass-delivery rates and TAN-mass-reduction rates for a backwash interval of 24 hours. An occlusion-induced reduction in mass transport does not, therefore, appear to impose a critical limit on nitrification.

Solids decay results in the solubilization of biochemical-oxygen demand (BOD) and TKN (total Kjeldahl nitrogen). This can make a significant contribution to the overall level of soluble contaminants. Studies conducted on finfish fecal matter (Wang, 1995) and sludge from FBFs (Ning, 1995) indicated that when solids decay BOD and TKN are produced in direct proportion to their percentages in the solids. A similar result was observed during a study of waste-activated sludge (Matsuda *et al.,* 1988). Matsuda's work also indicated that there was no appreciable delay between the solubilization of the organic solids and ammonification of the organic nitrogen (i.e. the organic nitrogen expressed in TKN is converted to TAN upon solubilization of the solids).

Several studies indicate that solids excretions have a higher BOD:TKN ratio than soluble excretions (Ning, 1995; Wang, 1995; Wimberly, 1990). A detailed study of the characteristics of waste excretions from finfish indicated that the BOD:TKN ratio was about 3 for soluble excretions while it was 4.3 for the fecal solids (Wimberly, 1990). Thus, as SRT is extended, solids decay may significantly elevate the concentration of soluble carbon and increase the soluble BOD:TAN ratio (Golz *et al.,* 1996).

2.3 The effects of a long solids-residence time on bacterial growth

Longer SRTs probably foster increased heterotrophic populations, because of the larger availability of soluble carbon. The effects of competition between heterotrophs (i.e. bacteria that utilize organic carbon) and the autotrophs that perform nitrification has been widely reported in the literature (Metcalf and Eddy, 1991; Sharma and Ahlert, 1977). When the BOD:TKN ratio is elevated, heterotrophic bacteria enjoy an increased competitive advantage, and this can inhibit nitrification (Bovendeur *et al.,* 1990; Manem and Rittman, 1992; Siegrist and Gujer, 1987; Zhang *et al.,* 1995). Heterotrophic bacteria typically have higher growth rates (e.g. 3 d^{-1}) and specific yields (e.g. 0.6). In contrast, nitrifiers usually have a slower growth rate and a smaller specific yield, on the order of 2 d^{-1} and 0.2, respectively (Figueroa and Silverstein, 1992; Golz, 1997; Metcalf and Eddy, 1991). Because of these disparities, heterotrophic bacteria usually dominate a biofilm or bioparticle surface (Manem and Rittman, 1992), where they utilize oxygen before it reaches the underlying nitrifiers (Zhang *et al.*, 1995). Disturbing bacterial colonies, especially by the shearing of the outer layer of biofilm during backwashing, may diminish the stratification that favors heterotrophs (Manem and Rittman, 1992). The effects of shear on viable bacterial colonies in a FBF have not been studied, although shear and biofilm thickness may be major factors affecting FBF nitrification.

A long SRT is the result of infrequent backwashing, so bacterial colonies can develop without disturbance. This results in thicker biofilm and larger interstitial biofloc. Clearly, thicker biofilm and biofloc have a smaller surface area to volume ratio, and this decreases the oxygen-penetration depth and reduces the rate of bulk-TAN diffusion (Beccari *et al*., 1992). Larger aggregations of biomass also foster an increase in the endogenous metabolism of the bacteria, i.e. the internal production and consumption of soluble substrate (Dritl *et al.,* 1993). The combined effect of impeded diffusion and endogenous metabolism can have a profound effect on nitrification. It can, in fact, diminish the utilization of bulk TAN, to the extent that most of the oxygen diffusing into macro-particles is consumed for internally-generated substrate (Dritl *et al.*, 1993).

2.4 The effects of biomass age on nitrification

Research indicates that backwashing removes primary solids and biomass from the interstitial suspension in approximately equal percentages, with respect to their individual total mass (Chitta, 1993). This means that the average age of the interstitial biomass is nearly equivalent to SRT. Therefore, a bacteria whose maximum growth rate is lower than the reciprocal of the SRT will not be able to exist in suspension (Metcalf and Eddy, 1991). There is, then, a given SRT where suspended nitrifying bacteria will cease to reproduce, e.g. 12 hours, and the faster-growing heterotrophs will become numerically predominant. Similarly, there is a SRT below which even heterotrophic bacteria will not exist, e.g. 8 hours. At a sufficiently-small SRT, the interstitial solids will be almost wholly fecal matter.

The aggregate mass of primary solids is much larger than total biomass (Golz, 1997); and the primary solids do not have the affinity for attachment that is exhibited by the bacteria (Sharma and Ahlert, 1977). Consequently, attached solids are most significant with regard to the bacteria, in terms of the percentage of overall biomass represented and its contribution to biomass age. The average biomass age is generally referred to as mean-cell residence time (MCRT). Research has demonstrated that a MCRT well above the reciprocal of the maximum growth rate is required to achieve efficient nitrification (Metcalf and Eddy, 1991; Sharma and Ahlert, 1977). Published minimum MCRTs range from as low as 3 days (Sharma and Ahlert, 1977) to as high as 20 days (Metcalf and Eddy, 1991). A study by Sastry (1996) showed that gently-washed filters can achieve a high nitrification rate (328 mg/m^2-media/d) at a 0.9 day SRT. This is well below the recognized minimum MCRT, so it is clear that gently-washed filters retain a significant amount of biofilm following a backwash. In contrast, the aggressively-washed filter required a longer interstitial solids age (SRT = 3.5 days) to produce similar nitrification (340 mg/m^2-media/d). This SRT is near the minimum MCRT that will reportedly produce effective nitrification, i.e. 3 days (Sharma and Ahlert, 1977). This indicates that aggressively-washed filters rely more heavily on suspended biomass.

3. Model development[3]

The model is derived from the mass balance shown in Figure 1 and incorporates the following assumptions: (1) All solids are captured in the filter, which is a standard approximation for FBFs and a conservative assumption reflecting a worst-case condition with respect to solids degradation (Chen *et al.,* 1991; Malone *et al.,* 1993); (2) There is no uneaten feed, which was the accepted operating protocol for the systems modeled (Chitta, 1993; Sastry, 1996); (3) The FBF and culture-tank behave like completely-mixed reactors, which is reasonable in the context of the high volumetric exchange rates and the small differences between influent and effluent concentrations (Metcalf and Eddy, 1991).

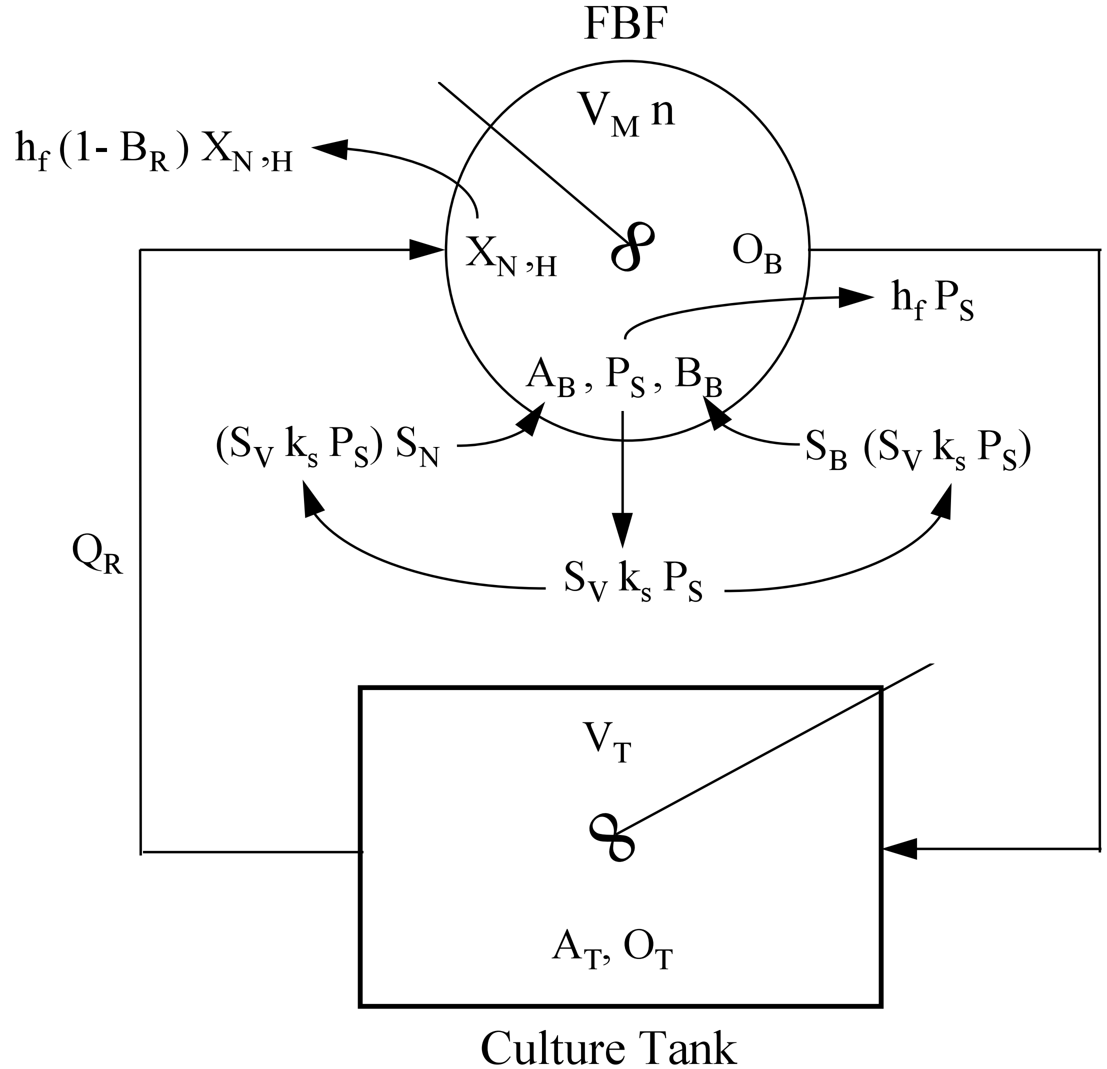

Fig. 1. Mass-balance diagram for the model showing the major variables.

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[3] This section presents the equations that are essential to a discussion of the relationship between backwash regime and nitrification. The complete model, applicable to packed-bed filters in general, is available from the corresponding author.

3.1. Primary solids

For the period between backwashes, primary solids consist of excretions that accumulate in the filter and are reduced by decay:

$$\frac{d}{dt} P_S = F_{LR}\ V_M\ E_S \left(10^6\right) - k_S\ S_V\ P_S \tag{1}$$

The term $F_{LR}*V_M$ is equivalent to the product of stocking density (S_D, kg fish/m^3), tank volume (V_T, m^3), and feed rate (F_R, kg feed/kg-fish/d). That is, $F_{LR}*V_M$ and $S_D*V_T*F_R$ both give the mass rate of feed given to the culture species. As the total suspended solids (TSS) reside in the filter, the portion that is volatile suspended solids (VSS) decomposes. This decay produces soluble BOD[4] and TAN at the rate of (k_s S_V P_S) S_B and (k_s S_V P_S) S_N (S_B and S_N are the BOD:VSS and N:VSS ratios). At the SRTs modeled, k_s is relatively constant (Rich, 1982) as are S_V (Chitta, 1993; Wimberly, 1990), S_B (Chen *et al.,* 1991; Wimberly, 1990), and S_N (Wang, 1995; Wimberly, 1990). Therefore, the mass of primary solids largely determines the quantity of soluble contaminants produced during decay.

The removal of primary solids during backwashing is specified in terms of the decimal fraction of the total mass. This is described by a discreet removal function, which is analogous to a Heaviside function (Kreyszig, 1993) performed at each backwash interval:

$$\left[H_S\right] = P_S\ h_f \quad \left[\text{Executed at integer multiples of } t * f_b\right] \tag{2}$$

The average age of the primary solids, and interstitial biomass, can be approximated as a function of backwash interval and harvest fraction (Coffin, 1993):

$$\text{SRT} = \frac{1}{h_f}\frac{1}{f_b} \tag{3}$$

In most FBFs, h_f is relatively constant for a given filter and can be manipulated only to a limited extent (Malone *et al.,* 1993). Consequently, backwash interval is the only effective means of controlling SRT. For a given system, SRT is a valid index of solids concentration because the two are directly related.

3.2. Biomass

The growth of nitrifying biomass that is limited by TAN and dissolved oxygen (DO) can be described by a Monod expression (Beccari *et al*., 1992):

$$\frac{d}{dt} X_N = \frac{\mu_{mn}\ A_B\ X_N}{K_{SA} + A_B}\ \frac{O_B}{K_{SO} + O_B} - k_d\ X_N \tag{4}$$

In occluded areas of the bead bed, the availability of externally-loaded TAN is certainly reduced. However, increased solids ammonification (Matsuda *et al.,* 1988; Wang, 1995) and heterotrophic metabolism (Dritl *et al.,* 1993; Sawyer *et al.,* 1994) in obstructed areas subsidizes soluble TAN levels. Because K_{SA} is an index of the overall local availability of TAN, it should remain relatively constant. Conversely, there is no compensating source for DO in occluded areas. Thus, one would

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[4] In general, BOD is discussed without subscripts, except with reference to specific calibration parameters. This is because the choice of five-day, twenty-day, or ultimate BOD is arbitrary, i.e. it will produce an equivalent result in the model with the appropriate choice of calibration parameter (Metcalf and Eddy 1991).

expect K_{SO} to increase with SRT, as reported in the literature (Beccari *et al.*, 1992; Siegrist and Gujer, 1987).

The growth of heterotrophic biomass under the conditions modeled will be limited only by BOD (Metcalf and Eddy, 1991):

$$\frac{d}{dt}X_H = \frac{\mu_{mh}\, B_B\, X_H}{K_{SB} + B_B} - k_d\, X_H \tag{5}$$

Research results indicate that the removal of interstitial biomass can be computed using Eq. (2) (Chitta, 1993). However, Eq. (2) will overstate biomass removal, because it does not account for the retention of attached bacteria (Golz, 1997). Thus, to adjust for biofilm retention, the biomass harvest must be described by the mass-balance equation

$$\left[H_X\right] = h_f\,(1 - B_R)\,X_{N,H} \quad \left[\text{Executed at integer multiples of } t * f_b\right] \tag{6}$$

It follows that MCRT can be approximated from SRT and B_R:

$$\text{MCRT} = \frac{\text{SRT}}{1 - B_R} \quad \left[0 \le B_R < 1\right] \tag{7}$$

Equation (7) illustrates how B_R acts to partition MCRT from SRT. In aggressively-washed filters, B_R is small, so SRT and MCRT are closely related. In the contrasting case of gently-washed filters, B_R is larger, so a reduction in SRT has a smaller impact on MCRT.

3.3. Biofilter total-ammonia nitrogen concentration

Biofilter TAN concentration is the result of mass exchange with the culture tank and, within the filter, solids ammonification and substrate uptake. Those quantities become concentrations relative to the interstitial volume, which is the product of the media's total volume and its intrinsic porosity:

$$\frac{d}{dt}A_B = \left(Q_R\, 1440\left(A_T - A_B\right) + S_V\, k_S\, S_N\, P_S - \frac{\frac{\mu_{mn}}{Y_N} A_B\, X_N}{K_{SA} + A_B}\, \frac{O_B}{K_{SO} + O_B} \right)\left(\frac{1}{V_M\, 10^3\, n}\right) \tag{8}$$

The completely-mixed reactor volume includes all of the biochemically-active volume--i.e. liquid, biomass, and primary solids (Metcalf and Eddy, 1991). Accumulating primary solids and biomass are part of the active reactor volume, although they lower Q_R which is correspondingly adjusted in the model. For very-large solids concentrations, inert matter probably causes some small actual reduction in porosity, but this is neglected.

The apparent areal nitrification-rate accounts only for the removal of externally-loaded TAN. It reflects the TAN mass-removal rate per unit surface area of the media, which is a product of the media volume and its specific surface area:

$$C_A = \frac{Q_R\,(A_T - A_B)}{V_M\, S_A} \tag{9}$$

3.4. Oxygen consumption

Oxygen consumed in filtration is a measure of the rate of total oxygen consumption within the filter:

$$\mathrm{OCF} = \frac{\mathrm{Q_R}\left(\mathrm{O_T} - \mathrm{O_B}\right)}{\mathrm{V_M}\ \mathrm{S_A}} \tag{10}$$

Oxygen consumed in nitrification is calculated as the product of the stoichiometric ratio of O_2:N and the measured TAN removal across the filter:

$$\mathrm{OCN} = 4.18\ \mathrm{C_A} \tag{11}$$

Autotrophic oxygen use for nitrification has been reported as 4.18 mg O_2/mg N in experimental studies of cellular synthesis (Hochheimer and Wheaton, 1991), and as 4.57 mg O_2/mg N for a purely chemical oxidation of N (Metcalf and Eddy, 1991). Applying the methods discussed in Sawyer *et al.* (1994) to the stoichiometry of fish excretions reported by Wimberly (1990) supports the ratio of 4.18 mg O_2/mg N.

The difference OCF - OCN, when combined with the product V_M S_A, describes the oxygen consumed in excess of that which is required for the removal of the externally-loaded TAN:

$$\mathrm{OCE_{AN}} = \left(\mathrm{OCF} - \mathrm{OCN}\right)\mathrm{V_M}\ \mathrm{S_A} \tag{12}$$

OCE_{AN} describes oxygen consumed mainly in bacterial respiration during the removal of BOD and TAN that is produced in the filter as a product of solids decay.

4. Model calibration

The model was calibrated to experimental data from two systems: a gently-washed BBF (Sastry, 1996) and an aggressively-washed PBF (Chitta, 1993). Both filters utilized 5 mm-diameter polyethylene-bead media (n = 0.35) and were modeled at a normalized V_M of 0.0283 m^3 (1 ft^3) (Golz, 1997). Particular data sets were selected to represent the behavior of each filter at three separate steady-state backwash intervals at peak F_{LR}s. Table 1 lists some of the conditions under which the experimental systems were operated and the results of the calibration.

Table 1
System values as they equated to observed versus modeled apparent areal nitrification-rates.

Filter	$1/f_b$ (hours)	F_{LR} (kg /m^3/d)	Q_R (L/min)	Observed C_A (mg/m^2/d)	Modeled C_A (mg/m^2/d)	Error (%)
BBF	8	32	28	328	325	0.9
	24	24	27	233	235	0.9
	48	24	25	185	194	4.9
PBF	12	24	35	161	165	2.5
	24	24	35	207	210	1.4
	48	24	35	340	336	1.2

The calibration constants were comprised of the system parameters, the solids-excretion rate and characteristics, and the Monod parameters. The system parameters (Table 2) and solids excretion rate and characteristics (Table 3) were based upon observed experimental values. The Monod parameters were fixed at the values listed in Table 4. The model depended continuously upon all the calibration constants, i.e. small changes in the constants produced small changes in the model's output.

Table 2
Selected dimensions and operating conditions for the experimental systems.

System	$1/f_b$ (hours)	Description	Variable	Value	Units	Reference
BBF	All	Culture-tank volume	V_T	1.62	m^3	Sastry, 1996
	All	Media surface area	S_A	1150	m^2/m^3	"
	8	Culture-tank DO	O_T	5.9	mg O_2/L	"
	24	"	O_T	4.8	mg O_2/L	"
	48	"	O_T	5.6	mg O_2/L	"
PBF	All	Culture-tank volume	V_T	4.53	m^3	Chitta, 1993
	All	Media surface area	S_A	1050	m^2/m^3	"
	All	Culture-tank DO	O_T	6	mg O_2/L	"

Table 3
Primary solids: Excretion rate, decay rate, and characteristics.

Description	Var.	Units	Calibr. Value	Literature Range	Reference
Solids excretion	E_S	Kg TSS/ kg feed	0.43	0.18-0.69	Gordon 1974, Murphy & Lipper, 1970; Page & Andrews, 1974; Raune *et al.*, 1977; Wimberly, 1990
Solids decay rate	k_s	d^{-1}	0.1	0.07-0.12	Ning, 1995; Wang, 1995
Solids VSS:TSS	S_V	unitless	0.88	0.88	Ning, 1995; Wimberly, 1990
SolidsBOD$_5$:VSS	S_B	unitless	0.15	0.09-0.39	Chen *et al.*, 1991; Wimberly, 1990
Solids TKN:VSS	S_N	unitless	0.05	0.038-0.089	Chen *et al.*, 1991; Wimberly, 1990

Table 4
Calibration values of selected Monod parameters.

Description	Var.	Units	Calibr. Value	Literature Range	Reference
Heterotrophic growth rate	μ_{mh}	d^{-1}	3	0.8-8	Metcalf and Eddy, 1991
BOD$_5$ half saturation	K_{SB}	mg BOD$_5$/L	30	25-100	"
Nitrifier growth rate	μ_{mn}	d^{-1}	2	0.3-3	"
TAN-N half saturation	K_{SA}	mg N/L	0.7	0.2-5	"
Nitrifier yield	Y_N	mg VSS/mg N	0.2	0.1-0.3	"

The biofilm retention factor and the oxygen half-saturation constant were the only variables in the final calibration, and their final values were dictated by the model. A unique value of B_R was required to achieve a minimally adequate quantity of nitrifying biomass at the shortest backwash interval for each filter. As expected, B_R was inversely related to washing energy (Table 5). Regarding the kinetic parameters, the preponderance of research indicated that they would remain approximately constant for the conditions modeled, with the notable exception of K_{SO}. The increase in oxygen-transport resistance that was necessary to achieve a calibration (Table 5), is consistent with the existing research.

The purpose of this study was to postulate a theoretical description of nitrification in packed beds, and to verify that description by calibrating a model to experimental data from FBFs. A suspended-growth Monod model was selected primarily for the following reasons: (1) packed beds in general, and FBFs operated at higher solids loadings, have solids concentrations that are similar to heavily-loaded suspended-growth reactors; (2) the large body of existing research that has reported values for the kinetic coefficients facilitate the model's calibration and verification; and (3) the kinetic coefficients, including B_R[5] and K_{so}, can be experimentally measured.[6] Developing a predictive model goes beyond the scope of this study, so the model was not validated (i.e. verified against predictions outside of the calibration limits).

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[5] B_R is obtained from the mass balance (Figure 1) on the bacteria.

[6] See, for example, Metcalf and Eddy (1991), Appendix H.

Table 5
Modeled values as they equated to oxygen-transport resistance

Filter (h_f, B_R)	$1/f_b$ (hours)	Solids Conc. (mg TSS/L)	SRT (days)	MCRT (days)	K_{SO} (mg O_2/L)
BBF (0.36, 0.8)	8	40×10^3	0.92	4.6	6.5
	24	80×10^3	2.8	14	17
	48	136×10^3	5.6	28	30
PBF (0.57, 0.5)	12	26×10^3	0.88	1.8	0.5
	24	50×10^3	1.8	3.5	5
	48	94x103	3.5	7	13

5. Results and discussion

5.1 Solids-residence time and nitrification

Experimental studies have demonstrated that longer SRTs ultimately lead to a reduction in apparent nitrification and a decline in the percentage of oxygen used to treat externally-loaded TAN (Chitta 1993; Sastry 1996; Wimberly 1990). The literature reviewed indicated that this observed relationship was due to several interrelated factors, all of which result in the nitrifying bacteria becoming oxygen limited: (1) Formation of macro-particles (Shammas, 1986), wherein bulk-substrate diffusion declines and oxygen is preferentially utilized for internally-generated substrate (Dritl *et al.,* 1993); (2) Soluble-substrate production during solids decay (Ning, 1995; Wang, 1995), which can elevate the soluble BOD:TKN ratio (Wimberly, 1990) and lead to increased heterotrophic populations which heightens competition for oxygen (Bovendeur *et al.,* 1990; Zhang *et al.,* 1995); and (3) Particulate occlusion, which leads to reduced and inhomogeneous dispersion, depriving occluded areas of bulk substrate (Golz, 1997). The model results were consistent with this interpretation, wherein the oxygen limitation increased with SRT.

K_{SO} represents the bulk DO concentration necessary to overcome every obstacle to the transport of oxygen to the nitrifying bacteria (Beccari *et al*., 1992; Metcalf and Eddy 1991). Figure 2 shows that K_{SO} was strongly correlated ($r^2 = 0.95$) to the ratio of OCE_{AN}:Q_R. The direct dependence of K_{SO} on OCE_{AN} probably mirrors the effects of preferential oxidation of the internal load and heterotrophic dominance in the competition for oxygen. The inverse relationship between K_{SO} and Q_R may reflect the dependence of dispersion on flow rate. OCE_{AN} and Q_R describe the biochemical and physical mechanisms, respectively, through which an increased solids concentration can limit the transport of oxygen to the nitrifying bacteria. Naturally, there is also a strong correlation between K_{SO} and solids concentration ($r^2 = 0.93$). Similarly, SRT is directly related to solids concentration for a given F_{LR}. The correlation of K_{SO} to SRT was also strong ($r^2 = 0.93$ when the regression consisted exclusively of data from the 24 kg feed/m^3-media/d F_{LR}, and $r^2 = 0.90$ when the data included the single 32 kg feed/m^3-media/d F_{LR}). Therefore, the oxygen limitation can also be referred to as a SRT effect[7]. The ability to mitigate this SRT limitation clearly depends upon the backwash regime of the filter, which entails a particular harvest fraction and biofilm-retention factor.

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[7] SRT is more convenient as an operation benchmark, because it can be easily computed (see Eq. 3).

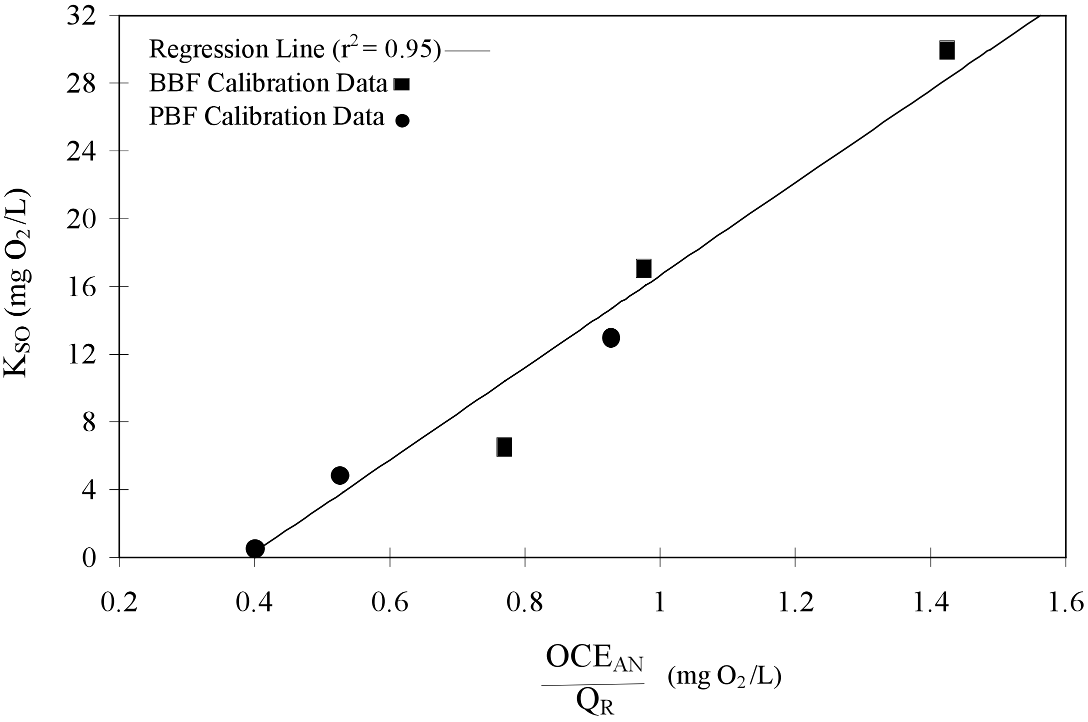

Fig. 2. The relationship of oxygen-transport resistance to: (1) OCE_{AN}, oxygen consumed for carbon oxidation and internally-loaded total-ammonia nitrogen (directly related); and (2) Q_r, recycle flow rate (inversely related).

5.2 The effects of backwash interval on nitrification rate in a gently-washed filter

Research has shown that gently-washed filters achieve their highest nitrification rates at relatively short backwash intervals, and filter behavior suggests that this is due to the combined effect of a low biomass-loss rate and a small harvest fraction (Cooley, 1979; Sastry, 1996; Wimberly, 1990). The gently-washed BBF modeled in this study had a harvest fraction of 36% (Coffin, 1993; Sastry, 1996), and the calibration indicated that biofilm retention was 80%. Model results support the view that the filter was not biomass limited at even the shortest interval ($1/f_b = 8$ hours). The model suggests that declining nitrification at longer SRTs was due to an oxygen limitation, which was precipitated by the relatively-low harvest fraction which resulted in rapid SRT growth.

Experimental studies have demonstrated that the 8-hour backwash interval equates to a 1 day SRT (Coffin, 1993; Sastry, 1996). The model results indicated that a backwash interval of 8 hours resulted in a MCRT of 4.6 days, with K_{SO} as 6.5 mg O_2/L. As Figure 3 shows, this corresponded to the highest observed C_A (325 mg N/m^2-media/d)[8] at the largest F_{LR} (32 kg feed/m^3-media/d) (Sastry, 1996). The model suggested that declining nitrification rates at the 24- and 48-hour backwash intervals resulted from the higher oxygen limitation incurred at SRTs of 2.8 days (K_{SO} = 17 mg O_2/L) and 5.6 days (K_{SO} = 30 mg O_2/L).

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[8] The discussion refers to experimentally-measured quantities whenever they were available.

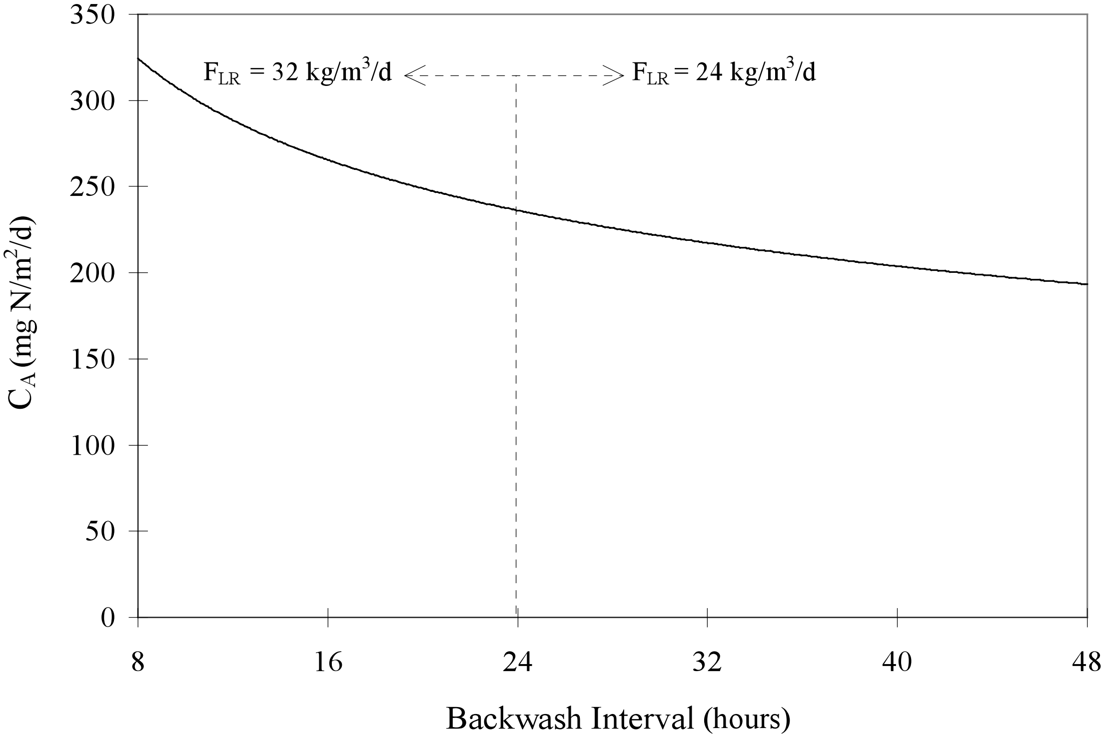

Fig. 3. The decline in apparent nitrification as the backwash interval was extended in the gently-washed filter. This reflects sufficient biomass at the shortest backwash interval and a rapid growth in the solids concentration as the backwash interval was extended.

5.3 The effects of backwash interval on nitrification rate in an aggressively-washed filter

Studies have shown that aggressively-washed filters require longer backwash intervals to produce optimal nitrification, and their performance suggests that this is due to substantial biofilm removal in concert with a large harvest fraction (Chitta, 1993; Malone *et al.,* 1993). The PBF modeled had a harvest fraction of 57% (Chitta, 1993), and the calibration results indicated that biofilm retention was 50%. The longer backwash interval that was required to produce optimal nitrification seems to have been the result of a higher biomass-loss rate, which limited populations of nitrifiers at shorter intervals. The larger harvest fraction, yielding slower SRT growth, allowed the backwash interval to be extended, which alleviated the biomass limitation. However, an interval was found beyond which SRT effects depressed nitrification. This is referred to as the critical backwash interval.

The model indicated that MCRTs of 1.75 and 3 days, which accompanied backwash intervals of 12 and 24 hours, were too low to provide optimal nitrification. As Figure 4 shows, the highest nitrification rate (340 mg N/m^2-media/d) occurred at a backwash interval of 48 hours. This corresponded to a MCRT of 7 days and a SRT of 3.5 days (K_{SO} = 13 mg O_2/L). The model results indicated that longer MCRTs could not offset the effects of the larger solids loadings incurred at backwash intervals of 60 and 72 hours, where SRTs were 4.4 days (K_{SO} = 22 mg O_2/L) and 5.3 days (K_{SO} = 27 mg O_2/L).

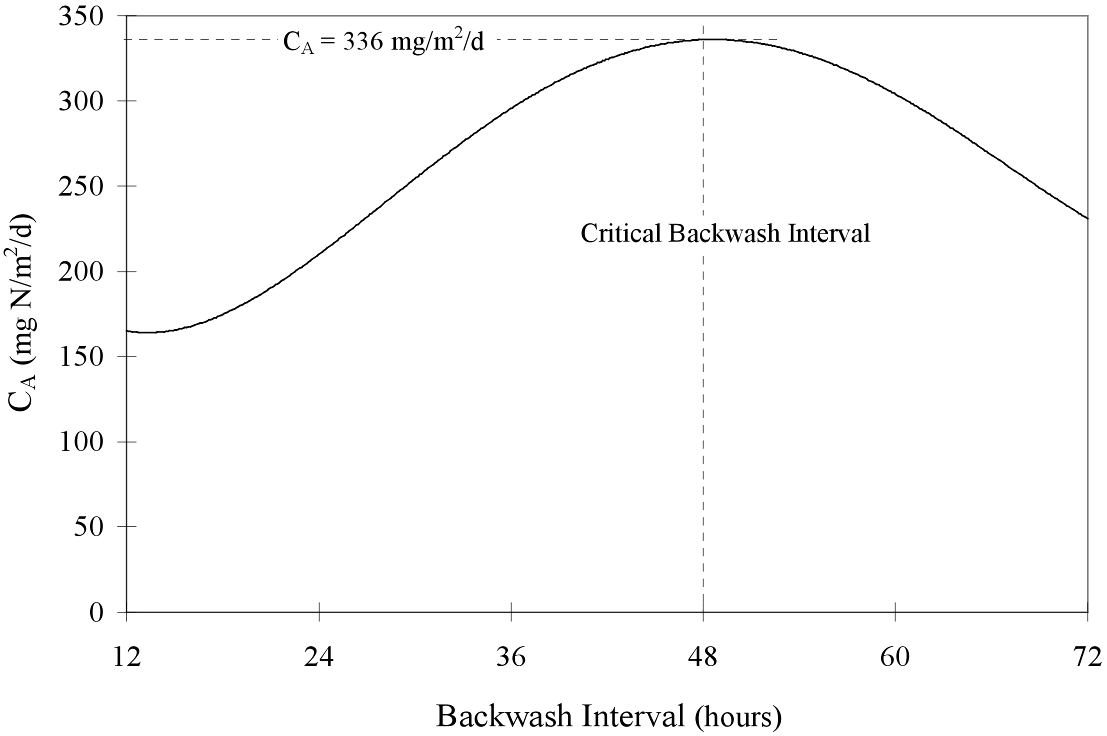

Fig. 4. The aggressively-washed filter initially exhibited increased apparent nitrification as the backwash interval was extended. The incipient increase is followed by declining nitrification once the critical backwash interval is exceeded. This reflects a biomass limitation at shorter backwash intervals and the effects of the solids loading beyond the critical interval.

6. Conclusions

Experimental results have shown that sustainable nitrification rates of 325-340 mg N/m^2-media/d can be achieved in bead filters at feed loading rates of 24-32 kg feed/m^3-media/d, with culture-tank TAN levels at or below 0.75 mg N/L (Chitta, 1993; Sastry, 1996). That research also demonstrated that gently- and aggressively-washed filters required very different backwash intervals to provide optimal nitrification. This paper discussed a model that was developed and calibrated to experimental data, to formulate a theoretical description of the behavior observed in FBFs.

When FBFs are operated at peak loadings, and the filter is washed infrequently or the harvest fraction is small, solids can limit nitrification. Solids accumulation leads to partial occlusion of the bed and is accompanied by a larger biofilm and biofloc thickness. These factors impede the delivery of bulk substrate. Solids decay, which occurs in direct proportion to the solids concentration, results in BOD and TAN production within the filter. The model results indicated that the end result of substantial solids accumulation is the preferential use of bulk DO for the oxidation of BOD and internally-produced TAN.

The gently-washed filter that was modeled achieved the best nitrification (325 mg N/m^2-media/d) at the shortest backwash interval studied (8 hours). The model results indicated that this was due to substantial biofilm retention (80%), which provided a sufficient biomass population, and a low harvest fraction (36%), which lead to rapidly-increasing solids concentrations as the backwash interval was extended.

The aggressively-washed filter exhibited optimal nitrification (340 mg N/m^2-media/d) at a critical backwash interval (48 hours). The model indicated that this single critical interval was due to lower biofilm retention (50%), which resulted in a biomass limitation at shorter backwash intervals, and a higher harvest fraction (57%), which yielded slower solids growth facilitating the longer backwash interval. The effects of solids accumulation inhibited nitrification at any backwash interval beyond 48 hours.

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