Developing Backwash Protocols for Floating-Bead Filters: A Model of Solids-Loading and Biofilm-Retention Effects on Nitrification[1]

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Introduction

Maintaining effective solids capture and nitrification can determine the success or failure of a recirculating aquaculture system (RAS). Although solids capture and nitrification are often performed sequentially, they are united in floating-bead filters. The use of bead filters in a RAS began at the Dworshak National Fish Hatchery (Cooley 1979). More recently, a bead filter was developed and tested by Wimberly (1990) at Louisiana State University (LSU). The Dworshak filter was pneumatically washed whereas LSU's was hydraulically washed. However, in both filters, increasing the washing frequency enhanced nitrification. These early studies established the importance of abridging solids residence time (SRT).

Solids capture impedes nitrification not only by exerting an internal ammonia and carbon load but ultimately by reducing flow through the filter. For extended SRTs, the increasing internal load causes filter oxygen demand to rise, while solids occlusion concomitantly reduces oxygen delivery. In terms of the solids-nitrification relationship, all bead filters belong to one of two classes: gently or aggressively washed, and their differences entail important implications for backwash regimen, i.e. backwash interval and duration. We define gently-washed filters as those where solids can be harvested with minimal biofilm removal. This means that SRT can be abbreviated without curtailing bacterial, or mean-cell, residence time (MCRT). In aggressively-washed filters, there is substantial biofilm detachment during backwashing. Therefore, SRT and MCRT are virtually equivalent, and this subverts attempts to increase nitrification by reducing SRT (Malone *et al*. 1993). Filter-class dissimilarities establish the need for different backwash protocols, which define the procedure for developing a backwash regimen to optimize nitrification.

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Bead filters, also referred to as expandable granular biofilters or EGBs, with several types of improved washing mechanisms are currently being studied at LSU. The bubble-washed bead filter (BBF) uses a hybrid pneumatic-hydraulic washing mechanism. By design, the BBF imparts a gentle wash, minimizing biofilm detachment while harvesting 30-50% of the total solids during each backwash. As shown in Figure 1, the BBF behaved like the earlier pneumatically- and hydraulically-washed filters: reducing the backwash interval enhanced nitrification (Sastry 1996).

The propeller-washed bead filter (PBF) was designed to exert an aggressive wash, to overcome initial resistance to filter-bed expansion in heavily-loaded systems. PBFs harvest 40-60% of the solids per backwash and biofilm detachment is substantial. As Figure 1 shows, in contrast to the BBF, an increase in PBF backwash interval improved nitrification (Chitta 1993). However, Chitta's study also demonstrated that when the backwash interval was extended beyond two days nitrification would ultimately decline, apparently because of internal-loading effects.

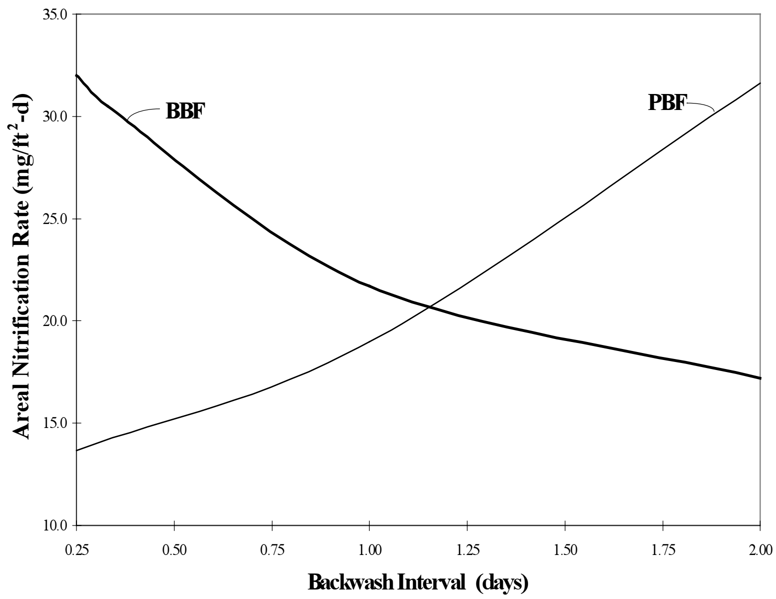

Figure 1. Nitrification rate as a function of backwash frequency (data from studies by Chitta 1993 & Sastry 1996).

This paper summarizes the preliminary results of a computer model. The model illustrates how backwash class determines biofilm retention and whether or not it is necessary to consider solids-loading effects. Model results indicate that: (1) In aggressively-washed filters, lower biofilm retention means that SRT and MCRT are nearly equivalent, making it necessary to increase backwash interval to achieve a MCRT capable of supporting a higher nitrification rate; (2) For the longer backwash intervals required by aggressively-washed filters, solids degradation with a concomitant increase in oxygen demand ultimately depresses nitrification; and (3) In gently-washed filters, higher biofilm retention establishes a partition between SRT and MCRT, permitting solids-degradation effects to be diminished with the proper backwash regimen. An appropriate backwash protocol will lead to a regimen that minimizes SRT within the constraints set by MCRT. For aggressively-washed filters, where MCRT and SRT are virtually equivalent, this means extending the backwash interval until the internal loading attenuates nitrification. In gently-washed filters, where MCRT is independent of SRT, backwash protocol will consist of decreasing the backwash interval until nitrification is optimized.

Model Development

This model was developed to explain the opposing nitrification-rate trends observed during similar backwash intervals in aggressively- versus gently-washed filters. The model is predicated on the assumptions that: (1) substrate uptake obeys Monod kinetics, in which μ_m, Y, and K_S are constants and (2) EGBs behave like completely-mixed reactors.

The complete model is comprised of a system of eight differential equations that describe the temporal change in solids, heterotrophic biomass, and nitrifying biomass in the filter, as well as culture-tank and biofilter total ammonia nitrogen (TAN), five-day biochemical oxygen demand (BOD_5), and dissolved oxygen (DO) concentration. Equations that are representative of the model, and that are most important to backwash protocol, are discussed below. Equation variables and their units are defined in Table 1, at the end of this section.

The accumulation of solids mass (M_S) in the filter is a result of solids excretion (R_{ES}) and net heterotrophic growth (R'_{GH}), while reduction is by solids decay (R_{DS}). The nitrifying-biomass growth term (R'_{GN}) makes a negligible contribution to the overall solids mass and is therefore excluded. For the period between backwashes, solids flux is described by the following equations:

$$\frac{d}{dt}M_S = R_{ES} + R'_{GH} - R_{DS} \qquad (1)$$

Where: $$R_{ES} = \frac{F_{LR}}{2.2}\, V_M\, E_S \qquad (1\text{-a})$$

R_{ES} is dependent upon feed loading rate (F_{LR}), the volume of filter media (V_M), and the solids excretion ratio (E_S), which is the cultured-species' solids excretion per unit mass of feed. V_M and E_S are constants for a given system and species. However, F_{LR} can be varied since it is related to stocking density (Losordo and Westers 1994).

$$R'_{GH} = \frac{\mu_{mh}\, X_H\, B_B}{K_{SB} + B_B} - k_d X_H \qquad (1\text{-b})$$

$$R_{DS} = M_S\, S_V\, k_S \qquad (1\text{-c})$$

R'_{GH} is the Monod term for net heterotrophic growth, and R_{DS} is the first-order volatile-solids (VS) decay rate (Metcalf and Eddy 1991).

The solids harvested ($[H_S]$) during a backwash is described by the fraction of solids removed (h_f), performed as a discreet adjustment at each backwash interval ($1/f_b$). This is analogous to a Heaviside function, as represented by the following equation:

$$[H_S] = M_S\, h_f \quad [\text{Executed at integer multiples of } t * f_b] \qquad (1\text{-d})$$

For the period between backwashes, the amount of nitrifying biomass (X_N) available to oxidize TAN in the filter is the result of substrate-limited net growth (R'_{GN})

$$\frac{d}{dt}X_N = R'_{GN} \qquad (2)$$

Where: $R_{GN} = \left(\frac{\mu_{mn} X_N A_B}{K_{SA} + A_B}\right)\left(\frac{O_B}{K_{SO} + O_B}\right)$ (2-a)

$$R'_{GN} = R_{GN} - k_d X_N \quad (2\text{-b})$$

R_{GN} is the Monod expression for nitrifier growth, when both TAN and DO are limiting, and adjusting R_{GN} for endogenous decay (k_d) yields net growth (R'_{GN}) (Metcalf and Eddy 1991).

Nitrifier harvest ($[H_N]$) is similar to solids harvest, with the important exception of a biofilm retention factor (B_R). B_R represents the relative amount of biofilm retained during a backwash and is an artifact of backwash class. Aggressively-washed filters, which deliver higher energy, will have a lower B_R, e.g. near zero. When B_R is identically zero, nitrifier and solids harvest will be equal, i.e. MCRT will equal SRT. As washing energy decreases, e.g. in the gently-washed filters, B_R will increase, and MCRT will become larger than SRT. The discreet reduction in nitrifying biomass is described by the following equation:

$$[H_N] = X_N\, h_f\, (1 - B_R) \quad [\text{Executed at integer multiples of } t * f_b] \quad (2\text{-c})$$

Biofilter TAN concentration (A_B) is a function of substrate uptake by the nitrifying biomass (R_{UA}), ammonification during solids degradation (R_{DA}), and mass exchange with the culture tank (R_{MA}). These quantities become concentrations relative to the biofilter's interstitial volume, which is the product of media volume (V_M) and porosity (n). TAN flux is described by the following equations:

$$\frac{d}{dt} A_B = \frac{-R_{UA} + R_{DA} + R_{MA}}{V_M\, n} \quad (3)$$

Where: $R_{UA} = \frac{R_{GN}}{Y_N}$ (3-a)

$$R_{DA} = R_{DS}\, S_N \quad (3\text{-b})$$

R_{UA} is the Monod term for biomass-limited substrate uptake (Metcalf and Eddy 1991). R_{DA} describes the instantaneous ammonification of solids during the decay of VS that have a given TKN:VS ratio (Matsuda *et al.* 1988).

$$R_{MA} = Q_R\, 5451 \left(A_T - A_B\right) \quad (3\text{-c})$$

R_{MA} is the mass exchange rate of TAN between the culture tank and the biofilter, which is dependent on recycle flow rate (Q_R) and the amount of external TAN load removed by the filter (A_T-A_B), where A_T is the culture-tank TAN concentration. R_{MA} can be described as an apparent nitrification rate since it does not include oxidation of the internal load, which results from solids ammonification.

C_A is the apparent-nitrification rate divided by the media's total surface area, which is a product of the media's total volume (V_M) and its specific surface area (S_A).

$$C_A = \frac{R_{MA}}{V_M\, S_A} \quad (4)$$

Model calibration was based upon data from two experimental systems, with one representative of each filter class. The systems were operated with similar carbon dioxide, alkalinity, temperature, and pH levels, which were conducive to nitrification (Allain 1988, Chitta 1993, Sastry 1996, Sharma and Ahlert 1977). Calibration data for the aggressively-washed class came from a study by Chitta (1993) while data for the gently-washed calibration originates from work done by Sastry (1996). System specific variables--feed rate, flow rate, influent oxygen concentration, and tank volume, were adjusted to reflect each system's unique conditions (Chitta 1993, Sastry 1996). Model calibration was made across filter classes, i.e. each kinetic constant was calibrated to a single value, constrained within literature values for similar systems.

Table 1. Definition of Variables

Eq. No.	Var.	Description	Units
(1)	M_S	Biofilter solids mass	mg TS
(1-a)	R_{ES}	Solids excretion rate	mg TS/d
(1-a)	F_{LR}	Feed loading rate	lbs feed/ft^3-media/d
(1-a)	2.2	Conversion from lbs of feed to kg feed	lbs/kg
(1-a)	V_M	Volume of filter media	ft^3
(1-a)	E_S	Solids excretion ratio	mg TS/kg feed
(1-b)	R'_{GH}	Net heterotrophic growth rate	mg VS/d
(1-b)	μ_{mh}	Maximum specific heterotrophic growth rate	1/d
(1-b)	X_H	Heterotrophic biomass	mg VS
(1-b)	B_B	Biofilter BOD_5 concentration	mg BOD_5/L
(1-b)	K_{SB}	BOD_5 half-saturation constant	mg BOD_5/L
(1-b)	k_d	Endogenous decay rate	1/d
(1-c)	R_{DS}	Solids mass decay rate	mg VS/d
(1-c)	k_S	Specific solids decay rate	1/d
(1-c)	S_V	VS:TS ratio	unitless
(1-d)	$[H_S]$	Solids harvest	mg TS
(1-d)	h_f	Harvest fraction	unitless
(1-d)	t	Time	d
(1-d)	f_b	Backwash frequency	1/d
(2)	X_N	Nitrifying biomass	mg VS
(2-a)	R_{GN}	Nitrifier growth rate	mg VS/d
(2-a)	μ_{mn}	Maximum nitrifier specific growth rate	1/d
(2-a)	A_B	Biofilter TAN concentration	mg N/L
(2-a)	K_{SA}	TAN half-saturation constant	mg N/L
(2-a)	O_B	Biofilter oxygen concentration	mg O_2/L
(2-a)	K_{SO}	Oxygen half-saturation constant	mg O_2/L
(2-b)	R'_{GN}	Net nitrifier growth rate	mg VS/d
(2-c)	$[H_N]$	Nitrifier harvest	mg VS
(2-c)	B_R	Biofilm retention factor	unitless
(3)	n	Porosity	unitless
(3-a)	R_{UA}	TAN utilization rate	mg N/d
(3-a)	Y_N	Nitrifier yield	mg VS/mg N
(3-b)	R_{DA}	Solids ammonification rate	mg N/d
(3-b)	S_N	TKN:VS ratio	mg N/mg VS
(3-c)	R_{MA}	Mass exchange rate (apparent nitrification rate)	mg N/d
(3-c)	Q_R	Recycle flow rate	GPM
(3-c)	5451	Conversion from GPM to L/d	L/d/GPM
(3-c)	A_T	Culture-tank TAN concentration	mg N/L
(4)	C_A	Apparent areal-nitrification rate	mg N/ft^2/d
(4)	S_A	Media specific-surface area	ft^2/ft^3

Results and Discussion

The solids-nitrification relationship is most critical in a PBF, where extending SRT is necessary to achieve the 3-7 day MCRT required for nitrification (Malone *et al.* 1993; Poduska 1973, cited in Sharma & Ahlert 1977; Timberlake *et al.* 1988). As SRT is increased, solids degradation creates a rising internal load. In the short term, this internal load reduces TAN and BOD_5 substrate limitation, making the filter more resistant to sharp variations in external loading. In the longer term, the internal load's associated oxygen demand will ultimately depress nitrification, defining the critical SRT, when nitrification reaches a maximum and thereafter declines. Critical SRT, and therefore backwash interval, will be higher for lightly-loaded systems but will decrease as system loading is intensified. However, for a given system and stocking density, the critical SRT will exist in an empirically-definable range, which can be related to the backwash interval and harvest fraction. This section describes a typical PBF, with a feed loading rate of 1.5 lbs feed/ft^3-media/d and a harvest fraction of 0.57 (Chitta 1993).

Figure 2 describes how solids concentration and MCRT in the filter increase with backwash interval. As the time between backwashes is extended, from once daily to once in three days, mean solids concentration grows from about 4% to 10% while MCRT increases from 2 to 5 days. Maintaining a bacterial-residence time on the higher end of this range will significantly increase the nitrifying biomass. The key to successful filter management is balancing the benefit derived from increasing MCRT with the escalating demands exerted by extending SRT, which increases the solids concentration.

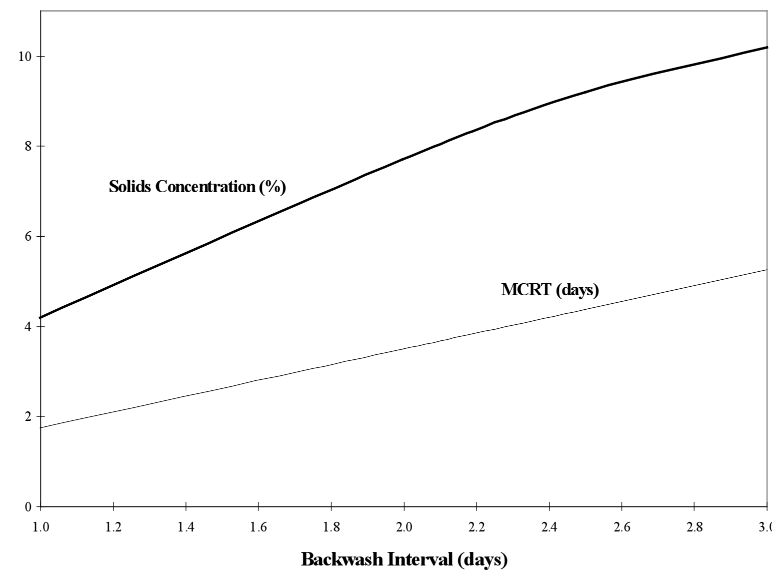

Figure 2. PBF mean-solids concentration and MCRT (B_R = 0; SRT = MCRT).

For a backwash interval of 1 to 3 days, as the solids decay, internal TAN load approaches, but does not exceed, the fish-excretion product. However, the internal BOD_5 load can surpass the soluble excretion rate in as little as 2 days, so the BOD_5:TAN ratio continually increases. Stoichiometric oxygen demand for total nitrification and BOD_5 uptake are similar, because of the larger oxygen requirement for nitrification. In the experimental system used to calibrate the model, biofilter effluent DO was held above 2 mg/L (Chitta 1993). Model results indicate that the oxygen delivered by filter flow exceeded stoichiometric demand, even for the 3 day backwash interval. Apparently, delivering stoichiometric quantities of oxygen and maintaining DO in the filter effluent does not ensure unimpeded nitrification: in the experimental system, nitrification rate increased for backwash intervals of up to 2.4 days, but then declined (Chitta 1993).

The curve in Figure 3 shows how nitrification rises and then falls, as the critical backwash interval is approached and then exceeded. The critical SRT that corresponds to the maximum nitrification rate is approximately

$$SRT_C = \frac{1}{h_f} * \frac{1}{f_{bc}} \qquad (5)$$

For the PBF described here, h_f is 0.57 and $1/f_{bc}$ is the critical 2.4-day backwash interval, making SRT_C equal to 4.2 days.

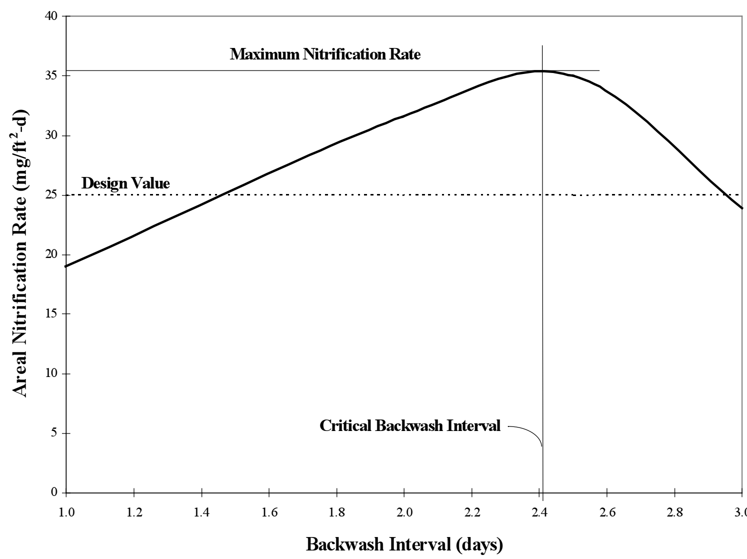

Figure 3. Critical backwash interval in a PBF (data from Chitta 1993).

A decline in nitrification following an increase in carbon:nitrogen (C:N) ratio has been documented in other biofilm research. Figueroa and Silverstein (1992) studied a rotating biological contactor and reported that: (1) nitrification declined linearly as BOD_5:NH_4^+-N ratio was increased; (2) particulate and soluble BOD_5 identically inhibited nitrification; and (3) Basin DO levels had no effect on nitrification rate. Bovendeur *et al.* (1990) studied a trickling filter used in a recirculating aquaculture system; they observed a linear decline in nitrification when COD:NH_4^+-N ratio was increased, at constant DO levels of either 3 or 7 mg O_2/L. Zhang *et al.* (1995), using micro-slicing and microelectrode techniques to study the competition for substrate and space in multi-species biofilms, reported that: (1) heterotrophic bacteria dominated the outer biofilm layer, while nitrifiers were most numerous near the attachment surface and (2) heterotrophs effectively competed with nitrifiers for oxygen (i.e. as glucose concentration was increased, oxygen-penetration depth decreased and biofilm NH_4^+-N concentration increased). The results of these studies strongly suggest that as C:N ratio is increased competitively-induced resistance to biofilm oxygen diffusion may be the main cause of declining nitrification. This would explain why the delivery of stoichiometrically sufficient quantities of oxygen and the maintenance of DO in the filter have little effect under a rising C:N ratio. If, in fact, competitively-induced resistance to oxygen transfer is the main mechanism of inhibition, an ideal nitrifying biofilm reactor should provide: (1) control of the particulate BOD_5 load; (2) active biofilm-thickness management; and (3) a larger MCRT for the bacteria closest to the media surface.

Biofilm retention can render the solids-nitrification relationship virtually irrelevant, if the proper backwash regimen is implemented. The ability to remove solids with only minimal biofilm detachment allows solids-loading effects to be curtailed while MCRT is preserved. In view of the C:N-ratio and the solids-loading effects, specifically the factors that limit nitrification, the gently-washed filter class may approximate an ideal nitrifying biofilter, whether or not the filter is used to capture solids. The biofilm-retention effect is clearly demonstrated when a reduction in backwash interval increases the nitrification rate.

Figure 4 depicts nitrification rate, MCRT, and SRT in a BBF with a harvest fraction of 0.35. The highest nitrification rate was 30.5 mg N/ft^2/d, achieved at a feed rate of 2 lbs-feed/ft^3-media/d, with a backwash interval of 0.33 days (8 hours). The corresponding cell-residence time can be approximated as

$$\text{MCRT} = \frac{1}{h_f} * \frac{1}{f_b} * \frac{1}{1 - B_R} \quad (6)$$

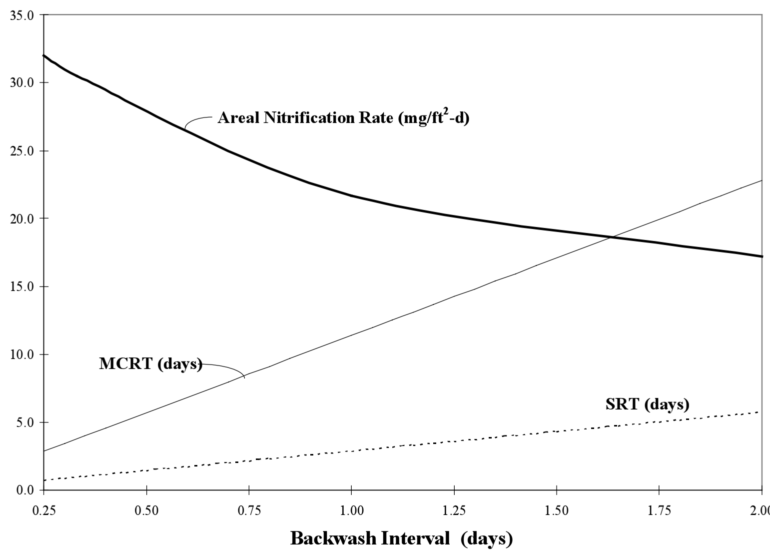

Figure 4. Areal nitrification rate and MCRT in a BBF (B_R = 0.8). (nitrification data from Sastry 1996; 0.25 d interval from regression).

For the BBF described here, with a backwash interval of 0.33 days, a harvest fraction of 0.35, and a biofilm-retention factor of 0.8, MCRT is about 4.7 days, while SRT is less than 1 day. Because nitrification rate increases linearly as backwash interval is decreased, it is possible that an even higher nitrification rate could have been achieved through a further reduction in backwash interval.

Conclusions

Research results demonstrate that areal nitrification rates above 30 mg N/ft^2/d can support feed loading rates as high as 1.5-2 lbs feed/ft^3/d, with the proper backwash regimen (Chitta 1993, Sastry 1996). When evolving a backwash regimen to improve filter performance, following the proper backwash-class protocol is of primary importance, because aggressively- and gently-washed filters respond opposingly to identical changes in backwash interval. In aggressively-washed filters, nitrification rate will generally increase as the backwash interval is extended. However, in gently-washed filters reducing the backwash interval will usually improve nitrification. For both filter classes, optimal backwash interval will be longer for lightly-loaded systems and shorter for more-heavily-loaded systems, because of the solids-nitrification relationship. Optimal backwash interval is, therefore, system specific, although following the appropriate protocol when developing a backwash regimen will lead to enhanced nitrification.

In aggressively-washed filters, SRT must be extended to achieve the MCRT required for efficient nitrification. Operationally, this can be executed by extending the backwash interval or by decreasing the harvest fraction. Ideally, backwash interval and harvest fraction will be managed in concert until maximum nitrification is achieved. Increasing the backwash interval will have the greater effect and should be implemented before reducing the harvest fraction. The interval should be extended incrementally, allowing the filter to reach equilibrium before changing the backwash frequency. Nitrification should increase with backwash interval until solids degradation begins to have a depressing effect. This procedure will define the optimum backwash interval, which corresponds to a critical SRT. A further increase in nitrification may accompany a reduction in the harvest fraction, achieved by decreasing the duration of the wash. Reducing the washing duration may also decrease biofilm removal because of the reduction in total washing energy. This may enable MCRT to exceed SRT, permitting a decrease in backwash interval, which will lessen the impact of solids decay.

Gently-washed filters retain more biofilm during a backwash, and therefore, SRT can be abbreviated without a severe reduction in MCRT. Improving nitrification should be approached by decreasing the backwash interval. Ultimately, the benefit of improving nitrification by decreasing the backwash interval must be weighed against the accompanying water loss. The effect of varying the washing duration, or intensity, will usually be more pronounced in gently-washed filters, because it represents a larger change in total washing energy, determining not only harvest fraction but biofilm retention Adjustments to washing duration or intensity should, therefore, be made incrementally.

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