ELSEVIER

Aquacultural Engineering 21 (2000) 233–246

aquacultural engineering

www.elsevier.nl/locate/aqua-online

Settling velocity characterization of aquacultural solids

Kevin B. Wong, Raul H. Piedrahita *

Biological and Agricultural Engineering Department, University of California, Davis, CA 95616, USA

Received 28 April 1999; accepted 18 October 1999

Abstract

A top-loading settling column is described and used to characterize the settling properties of the solids in the discharge water from a commercial rainbow trout production facility. Mass-based and phosphorus-based settling curves are presented. The median settling velocity on a mass-basis for the settleable solids was 1.7 cm s^{-1}. The median settling velocity for the settleable phosphorus was 1.15 cm s^{-1}. Manually stripping fecal material from rainbow trout resulted in settleable solids with a median settling velocity of 0.7 cm s^{-1}. Examination of the settling velocity curves show that halving the overflow rate (OFR) from 2 to 1 cm s^{-1} changes the removal efficiency from 0.61 to 0.73, an increase of about 20%. Halving the OFR again to 0.5 cm s^{-1} increases the removal efficiency to 0.81, an improvement of about 11%. Settling characteristics of aquacultural solids will vary from facility to facility. The methods described in this paper can be used to perform a similar type of analysis at other aquacultural sites, which may be growing other species under different management regimes.

Keywords: Aquaculture; Settling velocity; Suspended solids; Wastewater treatment; Phosphorus; Trout; Effluent; Solids removal; Particulates

1. Introduction

The aim of this paper is to present a methodology that allows for the characterization of the mass and phosphorus content of aquacultural solids in terms of settling velocity. Knowledge of the fundamental parameters of density, particle

* Corresponding author. Tel.: + 1-530-752-2780; fax: + 1-530-752-2640.
E-mail address: rhpiedrahita@ucdavis.edu (R.H. Piedrahita)

0144-8609/00/$ - see front matter © 2000 Elsevier Science B.V. All rights reserved.
PII: S0144-8609(99)00033-3

geometry, and particle-size distribution could be used to calculate the particle settling velocities. However, a single representative particle density cannot adequately describe aquacultural solids, measurement of the particle-size distribution is experimentally difficult, and particle geometry may be highly variable. In addition, information would still be lacking on how the phosphorus (nitrogen, heavy metal, therapeutant, or any other constituent of interest) is associated with a particular particle grouping. An empirically derived settling velocity curve incorporates information about the underlying parameters of density, geometry, and constituent content.

2. Background

Settling tests are conducted on wastewater samples to characterize how the particulate material in the sample will behave under the influence of gravity. A typical settling test involves collecting an effluent water sample, placing it in a tall clear column, and observing how the particles in the sample settle over time. These empirical tests provide the engineer with settling data specific to the waste stream under investigation and provide a basis for the rational design of gravity-based solid–liquid separation systems, such as sedimentation basins.

An informative way to display the information obtained from a settling test is by constructing a settling velocity curve (Fig. 1). The abscissa of this plot, V_s, is the settling velocity in centimetres per second. The ordinate is the fraction of solids (mass basis) that has a settling velocity less than or equal to the value on the abscissa (Tchobanoglous and Burton, 1991).

The overflow rate (OFR), volumetric flow rate entering the basin divided by the surface area of the basin, is a key parameter for sedimentation basin design. From the settling curve, one can choose an OFR (also known as the critical settling

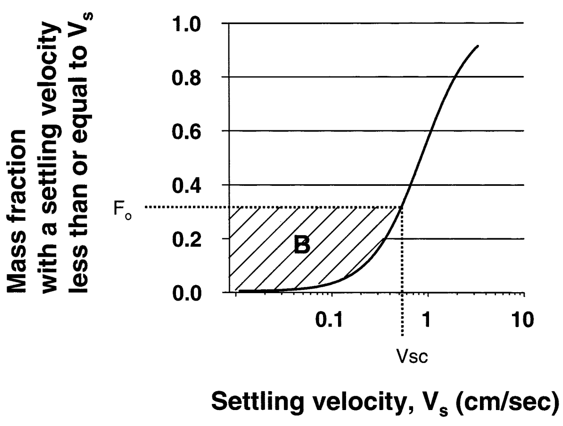

Fig. 1. A settling curve is an informative way to display settling velocity data. Refer to the text for descriptions of F_o, V_{sc}, and B.

velocity, V_{sc}) and then estimate the theoretical removal efficiency of the basin using the following equation (Reynolds and Richards, 1996):

$$\eta = (1 - F_o) + \frac{1}{V_{sc}} \int_0^{F_o} V dF \tag{1}$$

Where η is the removal efficiency (fraction of influent suspended solids that is removed), V_{sc} is the critical settling velocity, and F_o is the value on the ordinate corresponding to V_{sc} (Fig. 1). Eq. (1) can be rewritten as:

$$\eta = (1 - F_o) + \frac{B}{V_{sc}} \tag{2}$$

where B is the area of the graph shown in Fig. 1 and is equal to the integral in Eq. (1). Thus, the settling curve can be used to evaluate the trade-offs between the OFR and the particle removal efficiency of the sedimentation basin.

If the amount of particulate phosphorus (or any other constituent of interest) is also fractionated by settling velocity, then the theoretical removal efficiency of the particulate phosphorus can also be estimated. The ordinate of the characteristic settling curve would be the fraction of particulate phosphorus that has a settling velocity less than or equal to the value on the abscissa.

To construct the desired settling curve, a settling test is performed on a sample of the wastewater that would be entering the proposed sedimentation basin. A variety of settling column designs are in use in the USA and Canada, the most common being a clear acrylic column 1.5–2 m in height and 150–200 mm in diameter with sampling ports along the length of the column (Pisano, 1996). Initial homogeneity of the water sample is critical for the test; thus, various mechanical and manual methods have been employed to pre-mix the suspension within the column prior to the start of the sedimentation test. The use of such columns to determine settling velocities is described by Gregory and Zabel (1990).

Recently, the German company Umwelt und Fluid Technik (UFT) developed a simpler, more direct, and less costly settling test procedure (Pisano, 1996). The UFT-type settling column produces results that are reproducible and comparable with other methods. An important characteristic of the UFT-type column is that it can be used to study the settling properties of solids in either an unmodified or a pre-settled sample. This characteristic represents a significant advantage for use in aquaculture where suspended solids concentrations are highly variable depending on the type of operation and can be very low and difficult to measure. For example, flow-through raceway effluents typically have suspended solids concentrations under 10 mg l^{-1}, and their settling properties cannot be evaluated effectively using conventional settling columns. By adjusting the amount of material that is presettled, a UFT-type column can be used to analyze effluents with very different settling behaviors and solids concentrations (Michelbach and Weib, 1996). Fig. 2 is a schematic of the UFT-type column used in this study. Additional details on the UFT column can be found in Michelbach and Wohrle (1993).

The basic concept of the UFT-type settling column is to first separate out the settleable material and to use only this settleable material to construct the settling

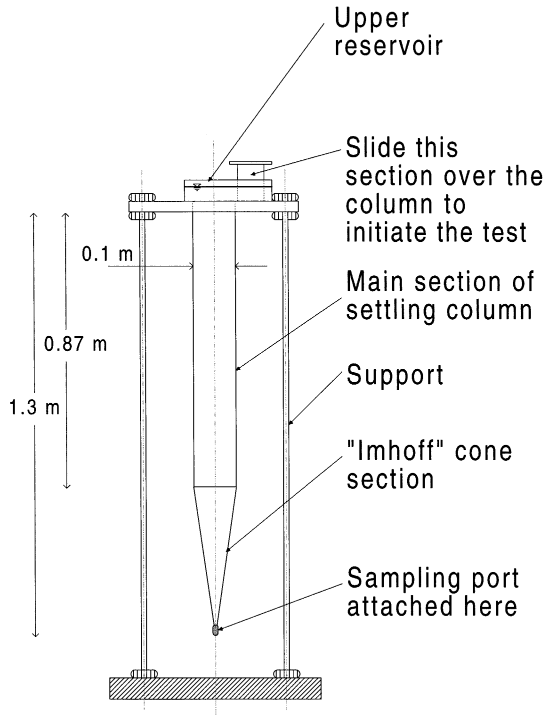

Fig. 2. A schematic of the UFT-type settling column used in this study. The column and upper reservoir were constructed of clear acrylic plastic.

curve. One method of preconcentrating the settleable material is to use multiple Imhoff cones. The wastewater sample is added to the Imhoff cones and allowed to settle according to Standard Methods (APHA, 1995). For very dilute wastewater more Imhoff cones are used to increase the amount of settleable material collected. The settled material is then carefully drained from the bottom of the Imhoff cones and used in the settling column. Another method is to use the column itself (Fig. 2) as a presettling chamber. The wastewater is added to the column and allowed to settle a specified amount of time. The settled material is then collected from the bottom of the column and the column is flushed and filled with clean water in preparation for the next stage of the test. The second stage of the test involves introducing the presettled material into the top of the UFT-type column and periodically withdrawing samples from the bottom of the column as described below.

3. Methods

A UFT-type settling column was constructed for partitioning the particulate material from an aquacultural water sample into characteristic settling velocities.

This top-loading settling column provided data so that a mass-based settling curve could be generated. After analyzing for mass, the settling-velocity fractioned samples were analyzed for total phosphorus so that a phosphorus-based settling curve could also be constructed.

3.1. Overview of settling column test procedure

The upper reservoir consisted of a rectangular box 24 × 12 × 10 cm (L × W × D) which was attached to the vertical settling column (Fig. 2). The top of the column was flush with the bottom of the upper reservoir. Water, at the same temperature as the aquaculture facility, was added to the apparatus until the column was completely filled and the upper reservoir was about 80% full. The presettled sample was introduced into a short section of acrylic pipe, which rested on the floor of the upper reservoir. The sample was gently stirred to suspend the solids, and at time zero the section of pipe was slid over the opening of the main column to allow the solids to fall.

An alternative method to introduce the sample into the top of the column is with a funnel submerged in the upper reservoir with its opening located above the column. A large diameter glass rod resting in the funnel opening can serve to trap the particulates in the wide portion of the funnel. Removal of the glass rod allows the particulates to fall into the column at the start of the test.

Samples were withdrawn from the bottom of the column at times t_1, t_2, t_3, t_4, …, t_n. The sample withdrawn at t_n represented the material that settled the length of the column between time t_{n-1} and t_n. Each test was run for 150 min with samples withdrawn at 10, 30, 90, 300, 3600 and 9000 s. Each sample was evaporated and dried to obtain the total solids. Alternatively, samples could be filtered and then dried to obtain the total suspended solids. The sum of the mass of samples 1…*n* was taken to be the total amount of mass that settled within the time frame of the test. From these results, the cumulative settling velocity curve was constructed.

Table 1 shows an example of a typical data set from a settling column experiment. The tests in this study were performed with a water temperature of 17°C. The settling velocity was calculated by determining how far the particles fell in a given time (i.e. the height of the column divided by the elapsed time). This value was then adjusted (see below) to account for the dropping water level which occurs when the sampling port is opened. The settling curve was constructed by plotting the settling velocity against (1 — cumulative fraction), i.e. the second column against the last column in Table 1.

3.2. Correcting for the dropping water level in the settling column

Opening the sampling port (located at the bottom of the column) causes the water level in the column to drop. An error, which becomes more pronounced as more withdrawals from the sampling port occur, will be introduced into the results if this effect is not taken into account. In this study, a failure to account for the dropping water level would lead to about a 5% discrepancy in the reported value

Table 1
Data from this trial (and others) were used in the development of the mass-based settling velocity curve[a]

Sampling event (s)	Settling velocity (cm s^{-1})	Dry mass concentration (mg l^{-1})	Mass fraction	Cumulative fraction	1 − [cumulative fraction]
10	3.91	3433.55	0.240	0.240	0.760
30	2.31	3590.95	0.251	0.492	0.508
90	1.03	3575.76	0.250	0.742	0.258
300	0.34	1938.81	0.136	0.878	0.122
3600	0.03	1678.41	0.117	0.995	0.005
9000	0.01	70.66	0.005	1.000	0.000

[a] Data from trout farm # 980708.

for the high settling velocity and about a 30% discrepancy for the low settling velocity values. In other words, the settling velocities (Y-axis) for the right-most data points in Fig. 3 would be incorrect by about 5%. The left-most data points would be off by about 30%.

Correcting for the dropping water level involves obtaining the volumetric flow rate ($cm^3\ s^{-1}$) by measuring the amount of water and the time it takes to withdraw that water during each sampling event. The average velocity at which the water level drops, v_i, would be this volumetric flow rate divided by the column cross section (cm^2). For example, say the sampling port is opened for t_p seconds each time an amount of water is removed from the bottom of the column. The particles collected after the third withdrawal from the column have experienced a drop in water level three times. Thus, when calculating the settling velocity we would subtract $(v_i)\cdot(3)\cdot(t_p)$ from the column height and then divide that by the elapsed time. In this case the settling velocity would be:

$$(\text{settling velocity})_{\text{3rd withdrawal}} = \frac{(\text{column height}) - (v_i \cdot 3 \cdot t_p)}{(\text{elapsed time})} \tag{3}$$

3.3. Temperature effects

Temperature affects the viscosity (and to a lesser degree the density) of water, which in turn influences the settling behavior of particles within the water. Performing the settling tests at the water temperature used in the aquaculture facility will provide the most accurate data for the design of a sedimentation system for that facility. When reporting sedimentation test data, it is recommended to note the temperature of the water in addition to other pertinent factors such as if the particles were subjected to any pretreatment or pumping before reaching the sampling site.

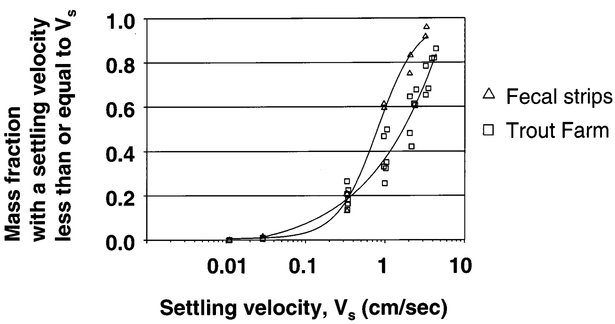

Fig. 3. Mass-based settling velocity curves.

3.4. Partitioning the particulate phosphorus by settling velocity

After the dry weights were measured, each sample was rehydrated using reagent-grade water and the phosphorus was extracted by digestion using the persulfate method (APHA, 1995). The phosphorus was then determined spectrophotometrically at 660 nm by reaction with paramolybdate using an automated flow injection analyzer (FIA). The laboratory performing these analyses reported a detection limit of 0.01 mg l^{-1} and reproducibility to within $\pm 10\%$ (DANR, 1998).

3.5. Settleable and non-settleable solids

Often, regulatory agencies are concerned with the total amount of solids or suspended solids removed, not just the settleable portion. In the UFT-type settling column tests reported here the solids in the water sample were first allowed to settle and only this presettled material was introduced into the settling column. Consequently, the settling curve that was measured only reflects these settleable solids. Analysis of the suspended solids remaining in the supernatant from the initial settling (prior to the column test), and the suspended solids remaining in the column after the 150 min was used to estimate the non-settleable fraction and to adjust the settling curve. By accounting for this non-settleable material the settling curve was adjusted to represent the curve for all of the material in the water sample, not just the settleable fraction. For example, if 27% of the solids in a given water sample were found to be non-settleable, then the first data point on the settling curve would be at location (0, 0.27). In other words, 27% of the material did not settle within the time frame of the test. The remainder of the settling curve would be based on the 73% of the solids that settled during the test. For this study, the fraction of settleable and non-settleable material was the average value obtained from multiple settling trials, in which the material still in suspension was quantified and compared to the material, which had settled.

The fraction of non-settleable material is influenced by a variety of factors including the amount of agitation and the age of the solids, and is expected to vary from facility to facility. Although Standard Methods (APHA, 1995) defines settleable solids as those which settle within a 60-min period, a longer settling time was used in this study so that the characteristic settling curves would span a larger range.

3.6. Study site

Multiple samples of recently settled material were taken over a 2-week period from the quiescent zone of the second raceway in a series of raceways at a commercial rainbow trout facility in Southern Idaho. The quiescent zone was a screened off area comprising the last 4.8 m of the downstream section of a 30-m long raceway. This screened off zone created a sedimentation area at the tail end of the raceway, just before the water exited via the overflow weir. Water depth at the quiescent zone was 0.9 m. From production records, the raceway was estimated to contain 21 600 individual fish with an average fish mass of 0.11 kg. The raceway immediately preceding the sampled raceway had approximately 19 450 fish with an average mass of 0.15 kg. The fish were fed an artificial pelleted diet (Rangen, Buhl, Idaho) via demand feeders. Approximately 6000 l min^{-1} of spring water fed the first raceway. The discharge from the first raceway fed the second raceway, and the discharge from the second raceway fed a third raceway. The water flowed through the three raceways in a single pass arrangement, no portion of it being recirculated.

3.7. Fecal stripping

Fecal material directly stripped from individual fish was analyzed in two trials. For the first trial, fecal material was collected from about 20–30 rainbow trout, each approximately 30–40 cm long. For the second trial, fecal material was collected from 187 fish, each 20–25 cm long. The fish were being held at the Hagerman Fish Culture Experiment Station (Idaho) and were anesthetized with MS-222 and then manually stripped of fecal material.

4. Results

The characteristic settling curves (mass basis) of the samples obtained for this study are shown in Fig. 3. The underlying data for a typical curve are summarized in Table 1 (mass basis) and Table 2 (phosphorus basis).

Solving Eq. (2) to obtain the theoretical removal efficiency of a sedimentation basin is facilitated by developing an expression to describe the settling curve. Using an iterative approach to find a least-squares fit, it was observed that a non-linear equation of the form:

$$y = a + \frac{b}{\left(1 + \left(\frac{x}{c}\right)^{d}\right)} \tag{4}$$

where y is the mass fraction with a settling velocity less than or equal to x, and x is the settling velocity, could describe the settling data obtained in this study (Jandel Scientific, 1992). Table 3 shows the equation parameters for the various settling curves. Different wastewaters will lead to different settling curves, the parameters in Eq. (4) may not be the most appropriate and even the form of Eq. (4) may differ. The objective at this stage of the analysis is to find a mathematical expression that best describes the settling data obtained.

For this study, Eq. (4) was found to be suitable and the equation parameters for the trout farm data in Fig. 3 were determined to be $a = -0.0508$, $b = 11.1030$, $c = 407.4861$, and $d = -0.5394$ with $r^2 = 0.95$. This expression can be used to approximate the settling curve for the region of settling velocities studied. By using this expression for the settling curve, Eq. (2) can be solved numerically and the theoretical removal efficiency can be determined. For example, an analysis performed with an OFR of 0.7 cm s^{-1} resulted in a removal efficiency of:

Table 2
Data from this trial (and others) were used in the development of the phosphorus-based settling velocity curve

Sampling event (s)	Settling velocity (cm s^{-1})	Phosphorus concentration (mg l^{-1})	Fraction	Cumulative fraction	1 − [cumulative fraction]
10	3.91	4.52	0.243	0.243	0.757
30	2.31	5.17	0.278	0.522	0.478
90	1.03	4.09	0.220	0.742	0.258
300	0.34	3.08	0.166	0.908	0.092
3600	0.03	1.52	0.082	0.990	0.010
9000	0.01	0.18	0.010	1.000	0.000

Table 3
Parameters for the equations used to describe the settling curves

Sample	Equation parameters				r^2	Figure
	a	*b*	*c*	*d*		
Trout farm (mass – basis)	−0.0508	11.1030	407.4861	−0.5394	0.95	Fig. 3
Fecal strip (mass – basis)	0.0064	0.9864	0.8080	−1.7316	0.99	Fig. 3
Trout farm (phosphorus – basis)	0.0056	5.0362	26.8169	−0.9242	0.99	Fig. 5
Fecal strip (phosphorus – basis)	0.0093	1.0061	0.8732	−1.6338	0.98	Fig. 5
Municipal wastewater (phosphorus – basis)	1.0532	−1.1989	0.1784	0.8992	0.99	Fig. 5

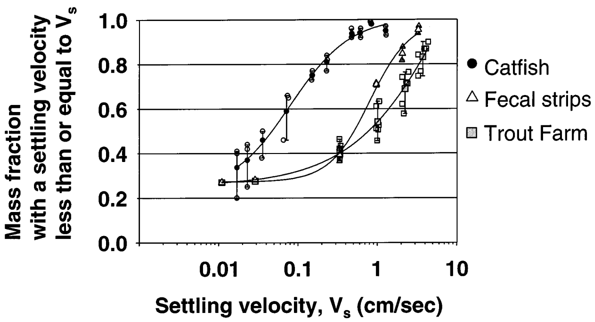

Fig. 4. Mass-based curves adjusted for the non-settleable material. Outlined symbols are data points, solid symbols are mean values, and the error bars represent the range.

$$\eta = (1 - F_o) + \frac{B}{V_{sc}} \tag{5}$$

$$\eta = (1 - 0.345) + \frac{0.084}{0.7} = 0.77 \tag{6}$$

Fig. 4 shows the mass-based data graphed with an empirically determined 27% non-settleable material (i.e. approximately one quarter of all the material, on a mass basis, did not settle during the presettling step or the column test). Characteristic settling data collected from a catfish culturing facility were also included for comparison. The catfish data (Chesness et al., 1975) were from a raceway facility which incorporated recirculation, contained an average total suspended solids level around 35 mg l^{-1}, and held catfish instead of trout.

Five of the settling tests (three from the rainbow trout grow-out facility and the two fecal strippings) were also analyzed for phosphorus content. A typical data set is presented in Table 2 and the characteristic settling curves (phosphorus basis) are shown in Fig. 5. The settleable phosphorus of a water sample taken from the influent to a municipal wastewater treatment facility was also fractionated by settling velocity (Hedges et al., 1998) and included for comparison.

5. Discussion

A hierarchy exists in the implementation of wastewater treatment methods. Initial concern is usually directed at the removal of settleable particulates (solids) from the effluent stream. Subsequent treatment then focuses on removing non-settleable material and other constituents such as dissolved nutrients. Integral to the overall effluent treatment train, rapid and efficient solids removal minimizes further breakdown of the particulate material and protects the more sensitive downstream treatment operations. An understanding of the sedimentation dynamics of aquacultural solids can lead to effective primary treatment strategies.

Settling velocity curves allow for a rational design methodology for settling basins and other primary treatment structures. The dimensions and flow rate into a settling basin can be used to compute the OFR of the basin. Comparison of the OFR with the settling curve establishes the theoretical removal efficiency of the basin, given the characteristics of the water to be treated. Examination of the settling velocity curves (Figs. 3–5) show that, depending on the OFR, small changes may result in very little or very significant changes in the overall removal efficiency of the sedimentation basin. Halving the OFR from 4 to 2 cm s^{-1} in Fig. 3 changes the removal efficiency for the settleable trout farm waste (as calculated by Eq. (1)) from 0.44 to 0.61, an improvement of about 39%. Halving the OFR again from 2 to 1 cm s^{-1} increases the removal efficiency to 0.73, an increase of about 20%. Halving the OFR again to 0.5 cm s^{-1} increases the removal efficiency to 0.81, an improvement of about 12%. Table 4 shows the predicted removal efficiency and the percentage improvement as the OFR is progressively halved. For a given flow rate into a sedimentation basin, halving the OFR represents a doubling of the basin's area.

Comparison of the mass-based and phosphorus-based settling curves (Figs. 3 and 5) shows that these curves are not dramatically different from each other, especially for low settling velocity values. For example, a sedimentation basin with an OFR of 0.5 cm s^{-1} would have a settleable solids removal efficiency around 0.81 on a mass basis and 0.93 on a phosphorus basis. In other words, under ideal conditions, about 80% of the solid material in the water (that could be removed by sedimenta-

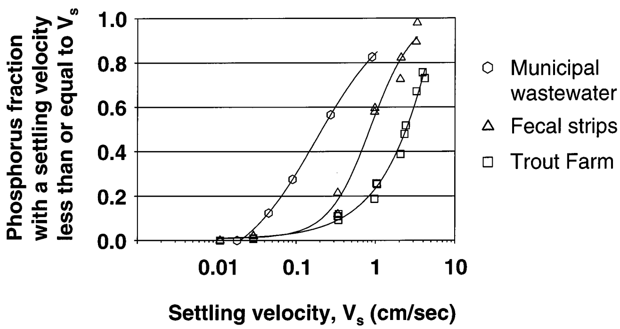

Fig. 5. Settleable phosphorus fractionated by settling velocity.

Table 4
Although decreasing the OFR improves the performance of the sedimentation basin, a 'diminishing returns' effect is observed

OFR (cm s^{-1})	Removal efficiency	Percent improvement (%)
4	0.44	–
2	0.61	39
1	0.73	20
1/2	0.81	11
1/4	0.87	7
1/8	0.91	5
1/16	0.94	3

tion) would be removed. From a phosphorus perspective, about 90% of the settleable phosphorus would be removed. This implies that a sedimentation system designed to mass-basis specifications, would be expected to have a similar (or slightly better) removal efficiency on a settleable phosphorus basis. This relationship, however, is expected to differ with differing feed composition, life-stage of the fish, or management practices.

Settleable solids in the sedimentation basin are still in contact with the water column and are still considered to be within the aquaculture 'system'. Unless removed from the system there will be continued breakdown of the solids resulting in smaller particles, solubilization of nutrients such as phosphorus into the dissolved state, and an increased oxygen demand due to biological activity.

6. Conclusions

Although the analysis presented in this paper is based on data from the particular effluent sampled in this study, the methods described can be used to perform a similar type of analysis at other aquacultural facilities which may be growing other species under different management regimes. Examination of the settling curves from this study suggests that a sedimentation basin should be designed with an OFR of about 0.5 cm s^{-1} or lower in order to capture about 80% of the settleable material. In more general terms, improving the OFR of a sedimentation basin can translate into big gains in terms of overall removal efficiencies, up to a certain point. The OFRs at which this 'diminishing returns' effect starts to occur is readily ascertained from the settling velocity curve.

Sedimentation tests, an important part of characterizing aquacultural particulate waste products, conducted with a top-loading settling column are well suited for aquacultural operations. The main advantages of the sedimentation test method described in this paper are: (i) The pre-concentration of the solids before the test allows a wider range of concentrations (even very dilute ones) to be measured, and the amount of pre-concentration can be adjusted to give suspended solids and nutrient concentration ranges that are much easier to measure. (ii) Use of the top-loading column circumvents the problem of having to keep the suspension completely homogenized at the start of the test, and also avoids the difficulty of trying to obtain the 'initial concentration' of the suspension and then relating each subsequent measurement to that value. (iii) By making individual withdrawals from the bottom of the column, the analysis of the sample is more straight-forward, especially when analyzing for some other constituent such as P or heavy metals. With other methods the analyst must divide the results from each withdrawal by the initial concentration, introducing a larger variability in the final result.

Acknowledgements

The authors would like to acknowledge the support of the US Department of Agriculture's Western Regional Aquaculture Center (WRAC), participating farms in California and Idaho, and Dr Ron Hardy and his capable staff at the Hagerman Fish Culture Experiment Station, Hagerman, ID.

References

American Public Health Association (APHA), 1995. Standard Methods for the Examination of Water and Wastewater, 19th ed. American Public Health Association, Washington, DC.

Chesness, J.L., Poole, W.H., Hill, T.K., 1975. Settling basin design for raceway fish production systems. Paper number 74-5005 presented at the American Society of Agricultural Engineers, June 23–26, 1974.

Division of Agriculture and Natural Resources (DANR) Analytical Laboratory, 1998. Determination of Soluble Phosphorus in Water—Automated Spectrophotometric. University of California, Davis, CA.

Gregory, R., Zabel, T., 1990. Water Quality and Treatment: A Handbook of Community Water Supplies, 4th ed. American Water Works Association, McGraw-Hill, New York.

Hedges, P.D., Becker, F.A., Smisson, R., 1998. The application of settling velocity as a parameter for characterising wastewater solids. Water Sci. Technol. 37 (1), 45–52.

Jandel Scientific Inc., 1992. TableCurve: Automated Curve Fitting Software. Jandel Scientific, San Rafael, CA.

Michelbach, S., Weib, G., 1996. Settleable sewer solids at stormwater tanks with clarifier for combined sewage. Water Sci. Technol. 33 (9), 261–267.

Michelbach, S., Wohrle, C., 1993. Settleable solids in a combined sewer system, settling characteristics, heavy metals, efficiency of storm water tanks. Water Sci. Technol. 27 (5–6), 153–164.

Pisano, W., 1996. Summary: United States 'sewer solids' settling characterization methods, results, uses and perspective. Water Sci. Technol. 33 (9), 109–115.

Reynolds, T., Richards, P., 1996. Unit Operations and Processes in Environmental Engineering, 2nd ed. PWS Publishing, Boston, MA.

Tchobanoglous, G., Burton, F., 1991. Wastewater Engineering: Treatment, Disposal, and Reuse, 3rd ed. McGraw-Hill, New York.