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Use of computational fluid dynamics (CFD) for aquaculture raceway design to increase settling effectiveness

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Abstract

A computational fluid dynamics model was used to evaluate the impact of potential raceway design modifications on the in-raceway settling of solids. Settling effectiveness was evaluated on the basis of the percentage of solids removed by settling relative to the mass of solids introduced into the raceway, with solids settling primarily in the quiescent zone (QZ).

The design modifications were applied to a simulated standard raceway (SSR). The SSR was a rectangular concrete raceway 30.2 m long, 3.0 m wide, 0.9 m deep, with a slope of 0.01. The raceway included a QZ of approximately 5.0 m (length), which was separated from the rearing area by a screen. The flow rate was 0.058 m^3/s.

For simulation purposes, six groups of particles were used to account for the total suspended solids (TSS). The representative particle sizes were 692, 532, 350, 204, 61, and 35 μm, for Groups 1–6, respectively. The smallest particles (Groups 5 and 6) are the most difficult to settle because of their low settling velocity.

After analyzing the velocity profiles obtained from the SSR and considering various design constraints, several raceway design alternatives were simulated. Among the alternatives tested, six designs were chosen based on their PSR values. The main feature in all the modifications presented is the addition of a baffle before the QZ or at the entrance of the QZ replacing the screen. The main purpose of adding these baffles was to increase the velocities under the baffle, which causes an increase in the accumulation of the solids after the baffle (in the QZ). According to the simulations, the highest PSR was obtained with the combination of a baffle and a screen under the baffle. The overall improvement of PSR with respect to the original system was small, with the most noticeable increases

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taking place for the smaller groups of particles, from 83 to 84%, 3 to 14%, and 1 to 5% for Groups 4–6, respectively. Further studies should include the evaluation of some of these alternatives in real raceways and the comparison of simulated and experimental PSR results.

Keywords: Raceway; Design; Trout; Sediment; Modeling; CFD

1. Introduction

In this study, a number of potential raceway design modifications were tested using a computational fluid dynamics (CFD) model of a "standard" aquaculture raceway. The model was created using a computer program called "simulation of sediment movements in water intakes with multiblock option" (SSIIM, Huggins, 2003; Huggins et al., 2004; Olsen, 2002). The model was used to simulate water flow and sediment transport in aquaculture raceways, such as those used for trout culture (Huggins, 2003). Sediment transport was examined on the basis of the percent of solids introduced into the raceway that settle and that are retained (percent solids removal efficiency (PSR)). The goal was to identify raceway design modifications that would result in an increased PSR value, representing a larger percentage of solids retained in the raceway and thus removed from the effluent. Recognizing the fact that fish activity typically results in the resuspension of a large proportion of the solids that settle in the section of the raceway where the fish are located, the design and modeling emphasis was placed on increasing PSR values in the quiescent zone (QZ), from which fish are excluded. From preliminary simulation trials, six potential raceway modifications were selected based on their high PSR values and ease of implementation in a real raceway.

A common feature in all of the modifications presented is the addition of a baffle before the QZ or at the entrance to the QZ replacing the screen. The main purpose of adding a baffle is to improve solids settling in the QZ by sweeping solids from the fish-growing section of the raceway (Boersen and Westers, 1986) and by forcing the solids to move (with faster velocities created by the baffle) close to the bottom of the raceway at the entrance to the QZ.

CFD simulations of aquaculture systems have been used to describe water flow and solids removal in circular tanks (Montas et al., 2000; Veerapen et al., 2002). Validation of the tank CFD model was carried out in a qualitative manner based on experimental observations (Montas et al., 2000). Montas and coworkers (Montas et al., 2000; Veerapen et al., 2002) agreed with some of the well-known advantages of using CFD modeling over laboratory physical models and found CFD models to be more flexible, faster to develop, and less expensive than physical models. However, they did not expect CFD models to replace physical models, but to efficiently extend laboratory results to large scales and altered geometries.

CFD also has been applied in studies of a turbot rearing tank (Rasmussen, 2002) to determine the mixing characteristics, the oxygen distribution, and the transport of organic material in rectangular tanks. In addition, CFD modeling has been used to simulate water flow velocity patterns and sediment conditions in aquaculture ponds (Peterson et al., 2000, 2001).

This study was focused on aquaculture installations that use flow-through raceways for the production of rainbow trout. The proposed designs have taken into consideration various industry constraints, such as maintaining fish stocking densities and minimizing complicated raceway design changes that may be difficult and expensive to implement.

2. Mathematical model and sediment transport calculations

The water flow velocity calculations are based on the Navier–Stokes equation for turbulent flow in a general 3D geometry for non-compressible and constant density flow (Olsen, 1991). SSIIM uses the k–ε turbulence model to predict the shear stresses near the walls and bottom of the raceway (Versteeg and Malalasekera, 1995). More details on how the k–ε model is used for calculating the turbulent shear stress is provided in Olsen's SSIIM manual (Olsen, 2002).

Model assumptions, which lead to specific model characteristics or simulation boundary conditions, include (Huggins, 2003; Huggins et al., 2004):

- a uniformly distributed inlet is used;
- the effect of fish on flow patterns and sediment transport is ignored;
- the screen configuration is simplified;
- sediments are released into the water at the surface of the raceway over a small section just prior to the screen due to the absence of fish;
- sediment resuspension is not included.

These assumptions were necessary given the current knowledge base and software limitations. The assumptions may limit the accuracy and potential direct application of model results. However, the design modifications are evaluated here on the basis of relative PSR calculations for the QZ. In addition, the validation of water velocity calculations was achieved by comparing measured and simulated velocities primarily in the QZ (Huggins et al., 2004). A detailed description of the sediment transport calculations used to obtain the sediment deposition rates is available elsewhere (Huggins et al., 2004).

3. Methodology

The raceway design modifications were applied to the simulated standard raceway (SSR, Fig. 1). The SSR was a rectangular concrete raceway 30.2 m long, 3.0 m wide, 0.9 m deep, with a slope of 0.01. The raceway included a QZ of approximately 5.0 m (length), which was separated from the rearing area by a screen. The flow rate was 0.058 m^3/s. At the time when the velocity data were being collected, the amount of feed distributed in the raceway was 45,400 g/d (Huggins, 2003). Based on this feed distribution, the production of solids in the raceway was estimated at 11,620 g solids/d using an assumed solids production of 0.3 g solids/g feed (Timmons et al., 2002). The effectiveness of particle settling in the raceway was estimated as the percent of solids removed (PSR) or settled in the QZ relative to the rate of solids produced from the feed. The PSR values were obtained

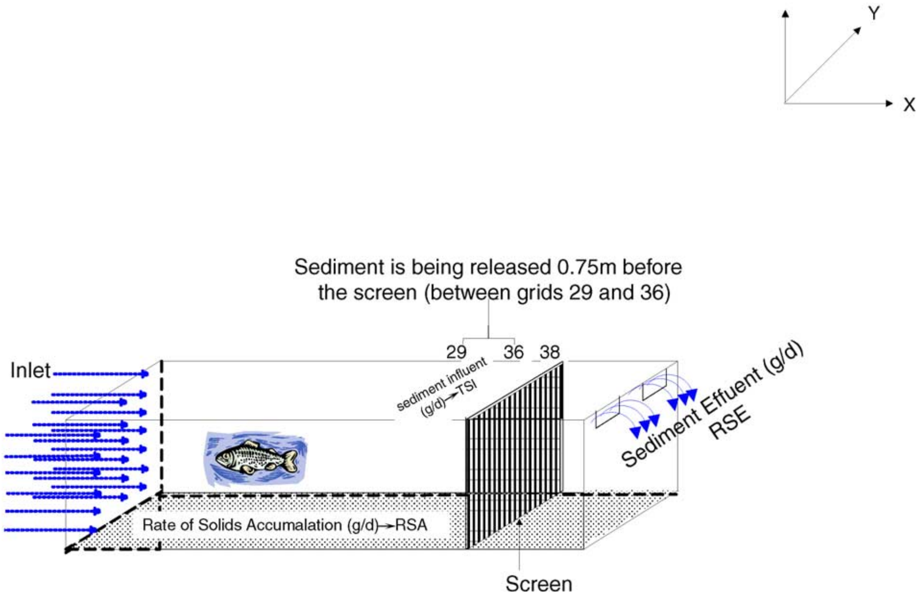

Fig. 1. Schematic diagram of the simulated standard raceway (SSR). The sediments are being released on the surface of the raceway 0.75 m before the screen.

for six particle size groups (Groups 1–6, Table 1) (Wong and Piedrahita, 2000). The groups suggested by Wong and Piedrahita are based on settled solids collected from a trout raceway and do not include non-settleable particles. The procedure used to determine the PSR is based on the calculation of the downward mass fluxes for the various particle groups across the bottom layer of the raceway and has been described in detail elsewhere

Table 1
Settling velocity distribution obtained from a trout farm (Wong and Piedrahita, 2000) and percent of solids removal (PSR) calculations for the simulated standard raceway (SSR) (Huggins et al., 2004)

Particle group no.	Settling velocity (m/s)	Mass fraction	Particle size (μm)	RSE (g/d)	RSA (g/d)	TSI (RSE + RSA) (g/d)	PSR (RSA/TSI) (%)	PSNR (%)
1	0.0391	0.240	692	0	3247	3247	100.0	0.0
2	0.0231	0.251	532	0	3396	3396	100.0	0.0
3	0.0100	0.250	350	1	3483	3484	100.0	0.0
4	0.0034	0.136	204	833	1007	1840	54.7	45.3
5	0.0003	0.117	61	1569	14	1583	0.9	99.1
6	0.0001	0.006	35	81	1	81	0.1	99.9
Total				2485	11146	13631	81.8	18.2

RSE: rate of solids exiting the raceway; RSA: rate of solids accumulated in the raceway; TSI: total solids entering the raceway; PSR: percent of solids removal efficiency; PSR: percent of solids no removed.

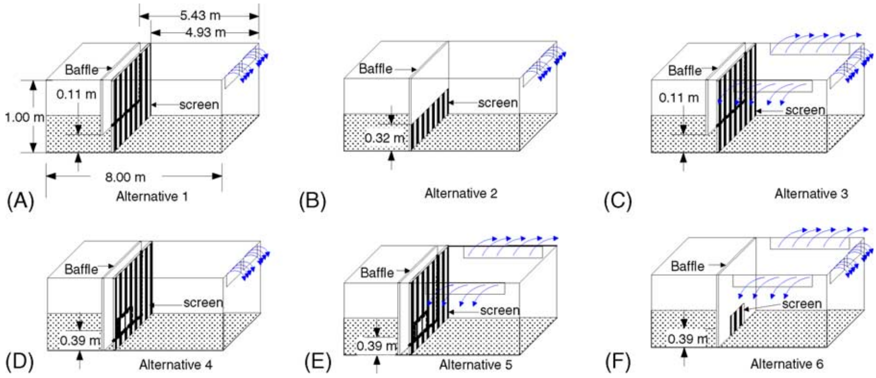

Fig. 2. Schematic diagram of the QZ for the design alternatives considered. The drawings show the approximate location and shape of the screen, baffle, and effluent weirs.

(Huggins, 2003, Huggins et al., 2004). The various design alternatives presented are shown schematically in Fig. 2.

3.1. Alternative 1: adding a baffle before the screen

The height of the open area under the baffle was calculated assuming a desired velocity under the baffle of 0.1 m/s (Boersen and Westers, 1986). This velocity was selected based on the recommended velocities for solids removal from raceways used for the culture of cold water species, such as salmon and trout (Boersen and Westers, 1986). In general, lower velocities do not move the solids adequately, and higher velocities break up the solids, making them more difficult to remove (Wagner, 1993):

$$Q = VA \Rightarrow A = \frac{Q}{V} = wh \Rightarrow h = \frac{Q}{Vw} \tag{1}$$

where h is the height of the open area under the baffle (m), Q the flow rate (0.0581 m^3/s), V the desired velocity under the baffle (0.1 m/s), and w the width of the baffle (3.05 m, the same as the width of the raceway). Eq. (1) yields, $h = 0.19$ m. However, the height of the baffle in the CFD model had to be adjusted to fit the grid dimensions used (Huggins et al., 2004), resulting in a height of 0.11 m (Fig. 2A) and an average velocity under the baffle of 0.17 m/s (Eq. (1)).

3.2. Alternative 2: screen only in the area under the baffle

Observations made when the velocity measurements were taken suggest that the fish tend to avoid the area within about 1.5–2.0 m of the screen. The placement of a baffle 0.5 m before the screen could further limit the fish to a smaller rearing area. Also, in terms of construction and maintenance it might be easier to replace the screen and baffle with only one structure that contains both (Fig. 2B). The dimensions of the area under the baffle were 3.05 m width and a height of 0.32 m, which yields an open area through the screen under the baffle of 0.49 m^2 and a corresponding average velocity through the screen of 0.12 m/s (Eq. (1)).

3.3. Alternative 3: adding a baffle before the screen and two weirs on the left hand side (LHS) and right hand side (RHS) of the quiescent zone

A baffle was placed in the same location as for Alternative 1 (Fig. 2A). The height of the open area under the baffle used in Alternative 3 was the same as the one used in Alternative 1, 0.11 m. Thus, the area and the calculated average velocity under the baffle (0.34 m^2 and 0.17 m/s) were the same as the ones for Alternative 1 (Eq. (1)).

Two weirs were added to decrease the magnitude of the vertical velocity component (Vz) in the QZ and the overall velocities in the vicinity of the weirs. These changes were caused by the increased area for the effluent. The two additional weirs had a length of 3.6 m each (Fig. 2C). Although the additional weirs are simulated as being directly on the LHS and RHS walls of the raceway, a similar effect may be achieved by the installation of troughs or gutters extending from the end wall and draining through the existing weirs. To simplify the calculations and reduce the time to obtain convergence the total flow rate of 0.058 m^3/s was divided equally into four outflows for each of the weirs, resulting in a flow rate of 0.014525 m^3/s per weir.

3.4. Alternative 4: adding a new baffle design, and maintaining the screen and two original weirs

The main objective of this new baffle design was to increase the trajectory of the particles as they move from the entrance to the QZ to the effluent (Fig. 2D). The baffle for Alternative 4 was placed at the same distance from the screen as in Alternatives 1 and 3. However, instead of having an opening extending the full width of the raceway (3.05 m) the opening was located in the middle and was only 0.93 m wide and 0.39 m high, resulting in a calculated average velocity through the baffle opening of 0.16 m/s (Eq. (1)).

3.5. Alternative 5: adding a new baffle design and two extended weirs on the sides of the QZ, and removing the two weirs on the end wall of the raceway

Alternative 5 is very similar to Alternative 4 as the same baffle design and screen were used, but the end wall weirs were replaced by extended LHS and RHS weirs, as in Alternative 3 (Fig. 2E). The dimensions of the open area under the baffle were 0.93 m $\times$ 0.39 m in height, resulting in an average water velocity of 0.16 m/s (Eq. (1)).

3.6. Alternative 6: replacing part of the screen with a new baffle design, adding two weirs on the sides of the QZ, and removing the two weirs on the end wall of the raceway

In this simulation the screen from Alternative 5 was eliminated and only a small screen was placed instead under the new baffle (Fig. 2F). Thus, the screen was 0.93 m wide and 0.39 m high with a net open area of 0.18 m^2 and a calculated average velocity of 0.32 m/s (Eq. (1)).

Table 2
Summary of PSR values for the simulated standard raceway (SSR) and the alternative raceway modifications

Particle group no.	TSI (RSE + RSA) (g/d)	SSR	Alternatives					
			1	2	3	4	5	6
1	3247	100.0	100.0	100.0	100.0	100.0	100.0	100.0
2	3396	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3	3484	100.0	99.6	99.7	98.6	99.4	97.9	97.5
4	1840	54.7	70.2	61.9	64.9	73.8	80.7	77.8
5	1583	0.9	7.5	4.4	13.4	11.3	53.0	50.7
6	81	0.1	2.2	1.1	20.2	3.7	49.3	47.6
Total	13631	81.8	84.5	83.1	81.0	85.4	91.1	90.3

All values are expressed as a percent of the total influent sediment fluxes.

4. Results and discussion

The effects of the proposed raceway modifications were simulated and evaluated in terms of the PSR for each of the six particle groups. The values of PSR, rate of solids exiting the raceway (RSE, g/d), total solids entering the raceway (TSI, g/d), rate of solids accumulation in the raceway (RSA, g/d), and percent of solids exiting the raceway (PSNR) obtained for the SSR are shown in Tables 1 and 2. The PSR for the SSR and the six design modifications studied are shown in Table 2. The PSR for Groups 1–3 were very close to 100% indicating that the particles with the three highest settling velocities would be removed almost completely regardless of the QZ configuration used among those tested here. Therefore, any improvements in overall PSR can only be achieved by improving the settling of particles with lower settling velocities (Groups 4–6).

For Alternative 1, there was an increase in PSR for Groups 4–6 and the overall PSR relative to that obtained for the SSR (Table 2). The increase in overall PSR results in a reduction of the overall RSE of 368 g/d or about 15% of the SSR value. For a series of five raceways, a typical configuration in many farms, the reduction in overall RSE would be 1840 g/d. The use of the baffle causes an increase in water velocity close to the bottom of the raceway, reducing particle settling prior to the QZ and forcing them into the QZ. In addition, the low vertical velocities in the QZ cause a large fraction of these particles to settle in the QZ, resulting in an increase in the PSR and a reduction in the RSE.

The PSR for Alternative 2 remained at 100% for the first three groups of particles but was slightly lower when compared to Alternative 1 for Groups 4–6 (Table 2). The overall RSE of Alternative 2 was 176 g/d lower than that for the SSR (Table 2).

The velocity profiles for Alternative 2 are presented at different levels of the raceway to illustrate the velocity simulations obtained and the velocity profiles for different locations in the raceway. Three levels are shown of 16 simulated in the vertical direction (Huggins et al., 2004) (Fig. 3). These are: Level 2, (3 cm from the bottom of the raceway), Level 7 (mid-depth), and Level 16 (surface of the raceway). Uniform flow patterns are observed at Levels 2 and 7 due to the use of a baffle that extends the full width of the raceway. The simulations also show the increase in velocities directly downstream from the openings in the screen. Backflows caused by the baffle are observed for Level 16, on the surface of the raceway (Fig. 3).

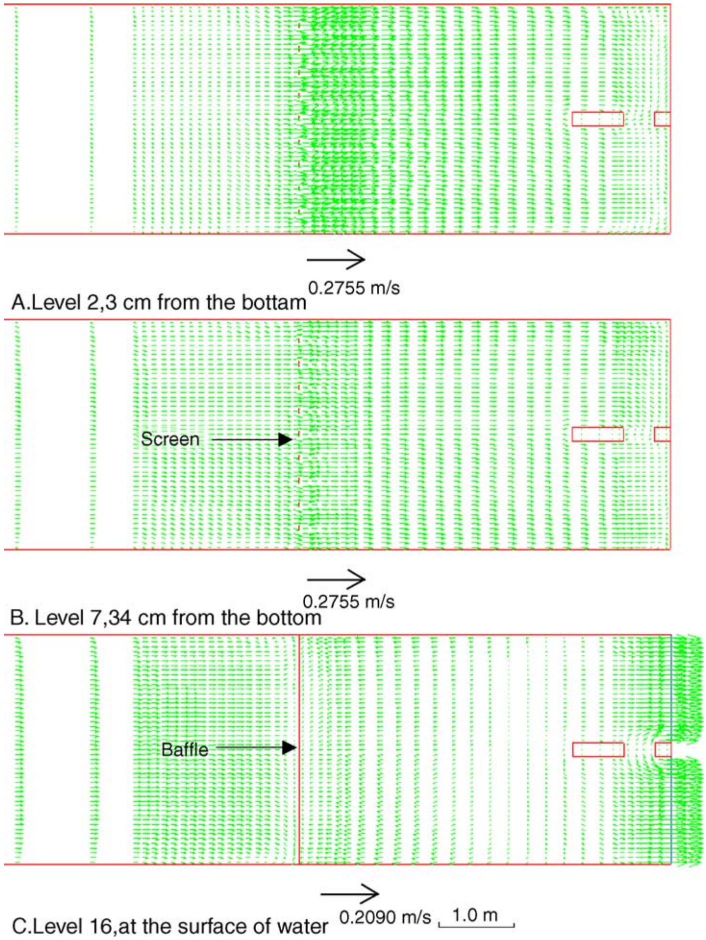

Fig. 3. Top view of velocity flow patterns at the outlet area for Alternative 2. Each drawing has a different scale for the velocity vectors. From Levels 2 to 7 there is flow through the screen (area under the baffle), and from Levels 8 to 16 there is a solid wall (baffle).

For Alternative 3, the PSR results for Groups 5 and 6 were higher than for the previous alternatives but the overall PSR was very slightly lower than that obtained for the SSR (Table 2). Although the addition of the weirs on the LHS and RHS caused a reduction to the horizontal and vertical velocity components in the QZ (Huggins, 2003), the drop was not sufficient to cause a decrease in the overall PSR.

The overall PSR for Alternative 4 was higher (85.4%) than for the previous alternatives (Table 2). This increase in the overall PSR can be attributed to the modified baffle design. The flow patterns for Alternative 4 show high velocities towards the middle section of the QZ and some backflows towards the LHS and RHS of the raceway (Fig. 4).

The PSR results for Alternative 5, with extended weirs and the new baffle, were higher than for all previous alternatives (Table 2). Also the overall RSE for Alternative 5 was

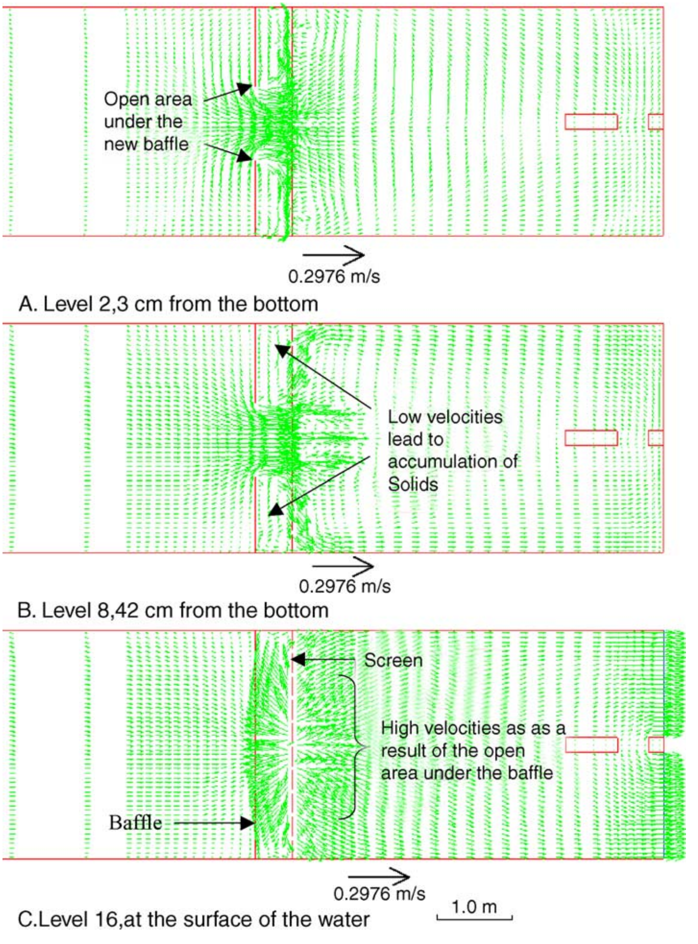

Fig. 4. Top view of velocity flow patterns at the outlet area for Alternative 4. From Levels 2 to 8 there is free flow through the open area under the baffle (width 0.98 m $\times$ 0.32 m height), and from Levels 9 to 16 there is a solid wall (baffle).

lower than for any other alternative. The total mass of solids exiting the raceway was 1213 g/d, which is about 1267 g/d less than for the SSR (about 51% of the SSR value). Also, in a series of five raceways 6335 g/d (6.3 kg/d) of sediments would not be discharged with the effluent when compared to the SSR model. Although the reduction in solids exiting the raceway may appear small in magnitude, it represents a substantial reduction in the proportion of the Groups 1–6 solids exiting the raceway when compared with the SSR. The velocity profiles for this alternative are similar to the ones for Alternative 4 (Huggins, 2003).

The PSR results for Alternative 6 were higher than for the SSR and the other alternatives except Alternative 5, especially for Groups 5 and 6 (Table 2). The overall RSE of Alternative 6 was 1158 g/d lower than for the SSR or about 47% of the SSR value.

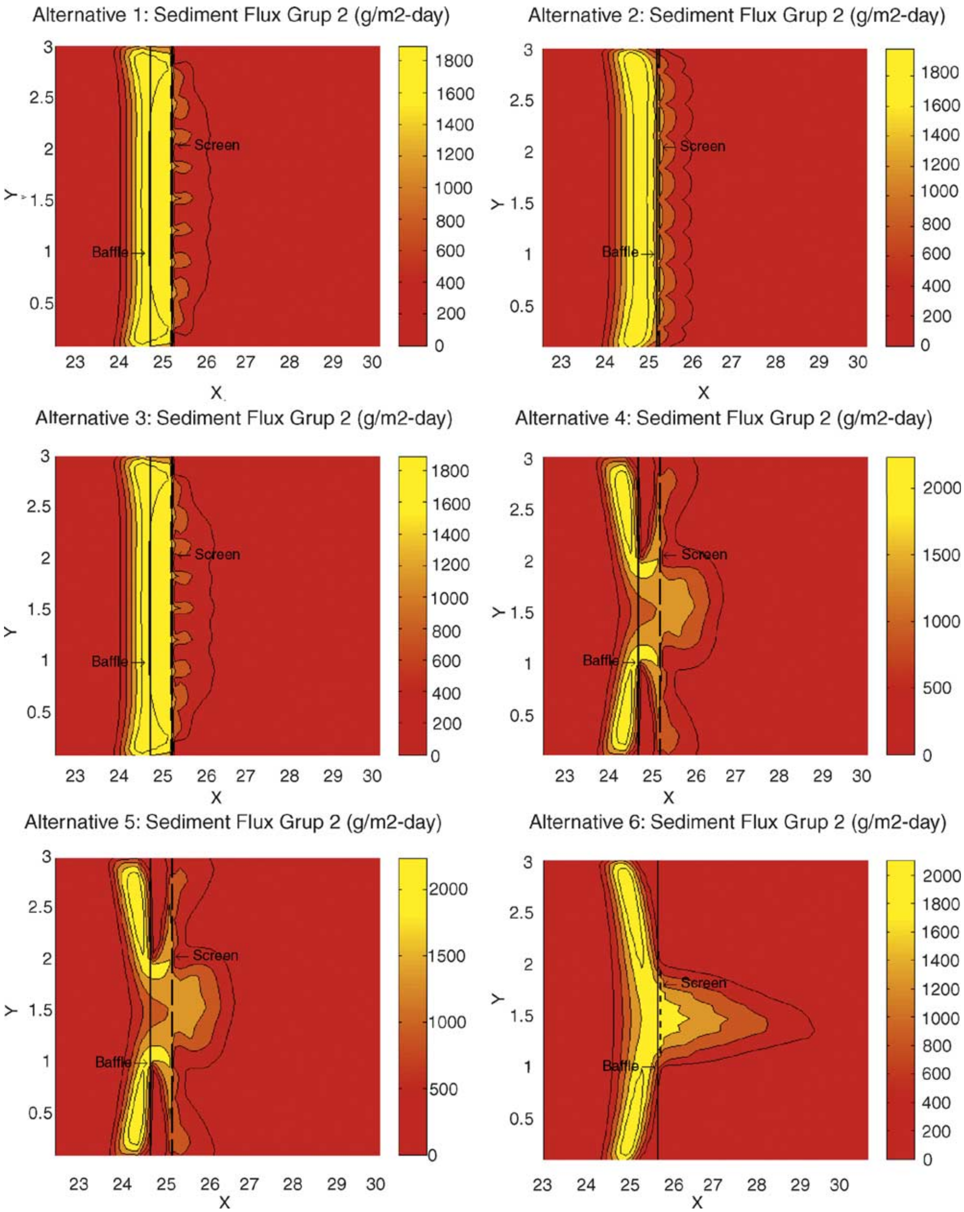

Fig. 5. Sediment fluxes for different design alternatives for particle Group 2, with a settling velocity of 2.31 cm/s and a diameter of 530 μm. The graphs represent settling on the bottom of the last 7.5 m of a raceway (The *x*-axis is the distance along the raceway and the *y*-axis is the raceway width. Flow is from left to right), corresponding mainly to the QZ. The graphs are not to scale. Red represents very low sediment fluxes and yellow corresponds to the maximum sediment fluxes for each of the design alternatives. The side bars for each of the graphs indicate the color correspondence of the sediment flux (g/m^2/d).

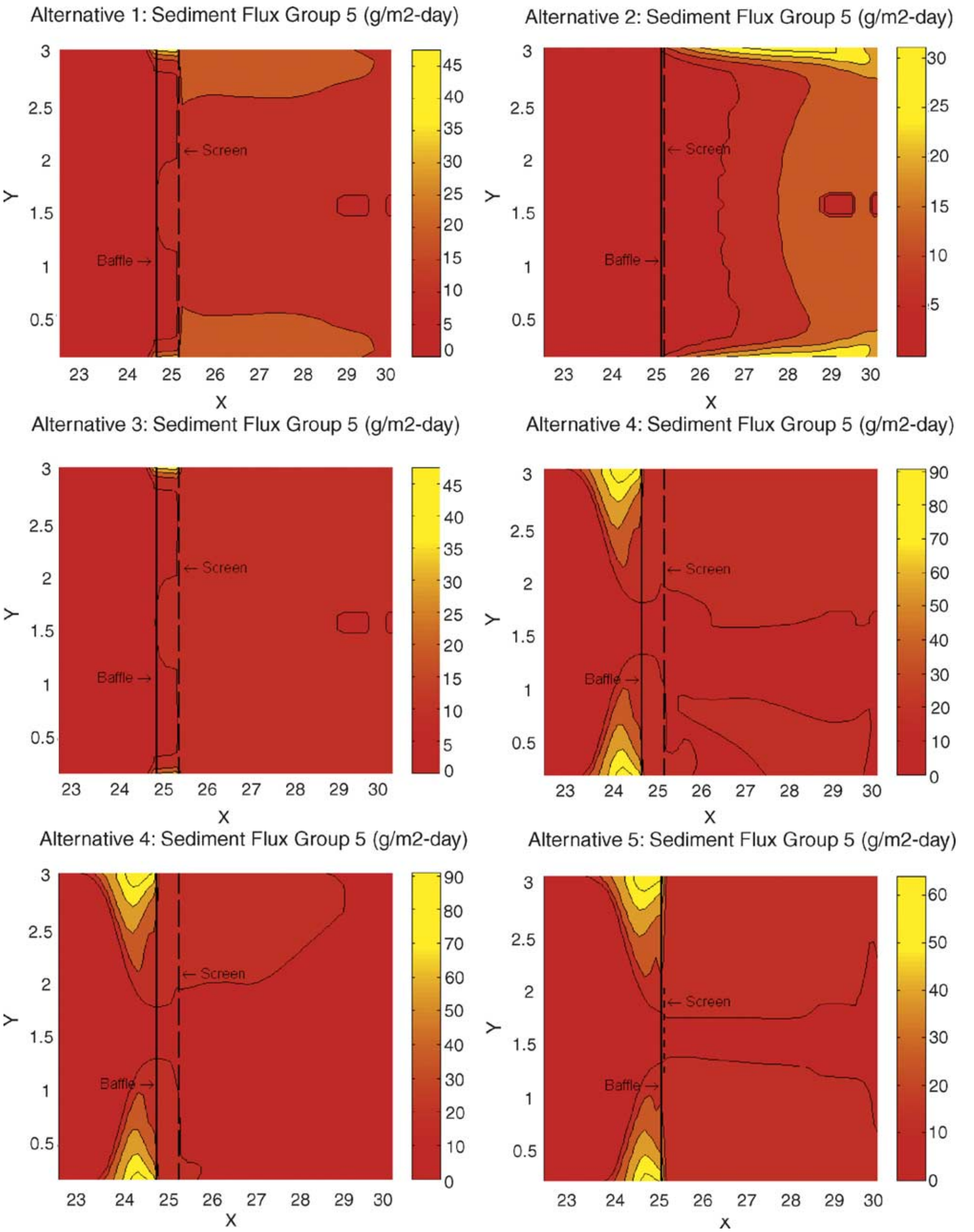

Fig. 6. Sediment fluxes for different design alternatives for particle Group 5, with a settling velocity of 0.03 cm/s and a diameter of 60 μm.

4.1. Settling patterns

A comparative analysis of sediment fluxes for different design alternatives is presented in Fig. 5 for Group 2, with a settling velocity of 2.31 cm/s and a diameter of 530 μm. For Alternatives 1–3, a large fraction of the Group 2 sediments settle before the QZ (Fig. 5). Also, as was previously mentioned, the turbulence created around the screen may cause some back-flow that would allow a large proportion of the bigger particles to settle in the fish rearing area.

Although Alternatives 4–6 resulted in similar values of total settling particle mass flux (Table 2), the flux patterns differed because of the hydraulic configuration of each design (Fig. 5). For example for Alternative 6, some of the sediments were displaced almost 4.0 m after the screen, while in Alternative 5 the maximum displacement of the Group 2 particles was about 1.5 m after the screen (Fig. 5).

The sediment flux for Group 5 (Fig. 6) is much lower than for Group 2 (Fig. 5), resulting in much lower PSR values (Table 2). The sediment contours for Groups 5 and 6 are very similar (Huggins, 2003), which also agreed with the results of the PSR calculations (Table 2).

4.2. Particle settling velocity distribution

The particle size distribution used in the analysis presented here was obtained by Wong and Piedrahita (2000) for solids collected at a trout farm. The particle settling velocity has a significant impact on the PSR values obtained for a given raceway design alternative. Therefore, the simulation results presented here are specific to the settling velocity distribution used. A change in the particle settling velocity distribution towards particles with higher settling velocity than those in Wong and Piedrahita's sample would result in increases in the PSR values. The converse is also true, suggesting that an important consideration in trying to improve the settling of particles within the QZ of raceways is to reduce the mass fraction of solids with settling velocities under 0.01 m/s (Table 1).

The results obtained with the current simulations provide guidance as to which might be the most promising alternatives to be tested in full size installations or using scale models. However, further testing and use of the model for raceway design modifications should be based on particle settling velocity distributions obtained for the conditions under which the raceway is operated. Most importantly, the particle size distribution is highly dependent on feed properties and these are constantly evolving. In addition, measurements of sedimentation rate and particle concentration in the raceway effluent should be made to be able to validate the sediment transport simulations for the SSR and the calculation strategies used to estimate sedimentation rates.

5. Conclusion

A number of possible minor raceway modifications were tested using CFD modeling to determine their potential impact on the PSR. An overall increase in solids settling in the raceway was achieved by the proposed design alternatives when compared to that of the

SSR model. The overall PSR increased from 81.8% for the unmodified raceway to 91.1% for Alternative 5. Although this is a minor change in the PSR, it results in an estimated reduction in the solids exiting the raceway of over 1210 g/d for each raceway such as the one analyzed here. This corresponds to a reduction of solids in the effluent of about 2.7% of the amount of feed applied to a raceway (45 kg) or about 51% of the solids in Groups 1–6 that exit the SSR.

The simulation results show quantitatively the effect of particle settling velocity on sedimentation effectiveness, with small differences in the particle settling velocity causing large changes in PSR values. The simulation results presented here are dependent on the settling velocity distribution used. Substantial improvements in PSR values can be expected if the settling velocity distribution of particles present in the raceway can be modified through improvements in the feed and feeding practices to produce particles with higher settling velocities.

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