Sediment Transport and Deposition in Reservoir Entrance

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Abstract. This numerical study will be using the provided MATLAB CFD code to study sediment transport and deposition in a reservoir entrance. As the code only covers water columns, the decreasing velocity of the flow at the entrance of the canal is simulated by decreasing the pressure forcing after a certain amount of time steps. The particle-based model is used to look at the behavior of particles in groups of four density ratios while the concentration-based model is used to generate a more general profile of sediment transport and deposition at different depths.

1. Introduction

This numerical case study will investigate sediment deposition behavior in dam reservoirs using principles of environmental fluid mechanics and sediment transport principles. Sediment deposition is a major component in the aging and reduced performance of dams, and it is particularly an issue with hydroelectric dams which see their power production capacity decreased as a result. With such infrastructure aging rapidly in the US and across the world, it is important to look at sediment deposition mechanics. This numerical study uses both particle-based and concentration-based models to simulate different scenarios in the given environment.

2. Methods and Models

Some assumptions were made to simulate the reservoir entrance. As seen in Figure 1, the entrance of our reservoir is accompanied by a sudden widening of our channel. Since we are assuming a constant height in our channel (Figure 2), this brings an increase in its cross-section area. Since our Flow Rate will stay constant, this brings a decrease in our flow velocity, per:

$$Q = V \times A$$

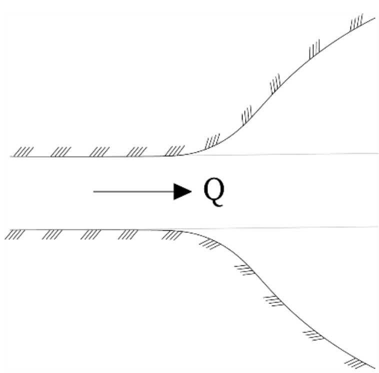

Figure 1. Top View of Reservoir Entrance

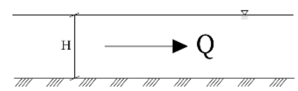

Figure 2. Side View of Reservoir Entrance

To reproduce this decrease in velocity in our water column, the pressure forcing is linearly decreased as a function of time until a certain threshold close to zero. The result is an exponential decrease in the flow velocity from the channel velocity. Figure 3 denotes the decrease in the mean flow velocity over time.
While a realistic flow velocity decrease would probably be smoother with a non-linear decrease in pressure forcing, I have chosen to keep a linear decrease in forcing for the sake of simplicity.

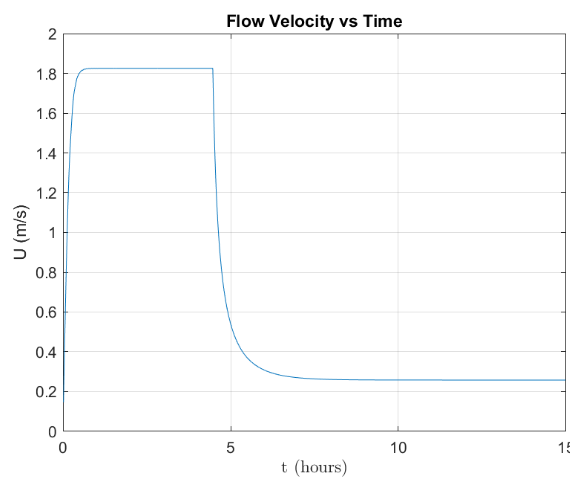

Figure 3. Mean Flow Velocity vs Time

Two models are used to cover a broader range of observations. The first is particle-based model that specializes in individually tracking the position of particles. This makes it good for getting a precise picture of particle travel paths but makes it computatuinally expensive for large populations of particles. The second is a concentration-based model which works better for getting a more general view of larger concentrations of particles in a fluid. Both models will be used to simulate a variety of scenarios.

2.1 Particle-Based Model

The following set of equations is implemented for individual particle tracking. Four equal sets of particles with different densities are used:

$$x_i(t+dt) = x_i(t) + U(z_i(t),t) \times dt \quad (1)$$

$$z_i(t+dt) = z_i(t) + w_s \times dt + \sqrt{2 \times K_z(z_i(t),t) \times dt} \times randn \quad (2)$$

Where,
x_i : x-position of the i-th particle.
x_z : z-position of the i-th particle.
t : current time step.
dt : the size of time step.
$U(z_i(t),t)$: Flow velocity at height z and time t.
$K_z(z_i(t),t)$: Turbulent Scalar Diffusivity at height z and time t.
$randn$: MATLAB function for random numbers from a normal distribution with 0 mean and variance of 1.
w_s : Settling velocity of the particle, defined as:

$$w_p = \left(\frac{\rho_s}{\rho_w} - 1\right) \times \frac{gD^2}{18\mu}$$

ρ_s/ρ_w: Solid to Water Density Ratio.
D : Particle Diameter.
μ : Dynamic Viscosity of Water.

These equations are accompanied by the following Boundary Conditions:

- If $z_i(t+dt) > 0$
  $$z_i(t+dt) = -z_i(t+dt)$$
- If $z_i(t+dt) < -H$
  $$z_i(t+dt) = -H$$

2.2 Concentration-Based Model

The concentration-based model is a modification of the scalar transport model, with the introduction of a deposition flux:

$$F_{dep} = w_s \times \frac{dt}{dz}$$

And of a resuspension flux:

$$F_{res} = 0; \quad if\ u^* < u_c$$

$$F_{res} = A_r(u^{*2} - u_c^2)$$

Where,
A_r: Erosion Coefficient
u^*: Friction Velocity
u_c: Critical Friction Velocity

3. Model Parameters and Initial Conditions

The following flow and sediment properties are used:
Sediment:

$$D = 0.0001\ m; \quad A_r = 1.25$$

Flow:

$$u^*_{crit} = 0.007\frac{m}{s}; \quad \frac{dP}{dx} = -0.0025; \quad \mathrm{K} = 0.4; \quad C_D = 0.0025$$

Model Parameters:

$$H = 5m; \quad N = 80; \quad dt = 60; \quad M = 900;$$

3.1 Particle-Based Model Parameters

We use a population of 400 particles separated into four categories by density ratios. The density ratios used are 1.05, 1.5, 2.25, and 5.0.

3.2 Concentration-Based Model Parameters

In our concentration-based model, we use two sets of densities and two column heights. We will look at cases of combinations of both variables. Our column is initialized with no concentration.

We choose low-density sediments with $\rho_s/\rho_w = 1.01$ and high-density sediments with $\rho_s/\rho_w = 3.5$. We will look at a shallow channel of H = 5m, and a deeper one at H = 15m.

4. Results and Graphs

4.1 Particle-Based Model

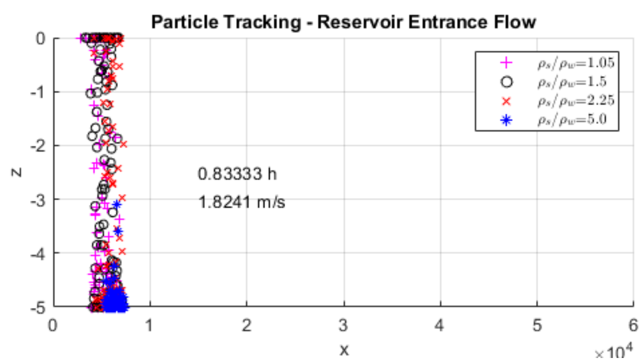

Figure 4. a

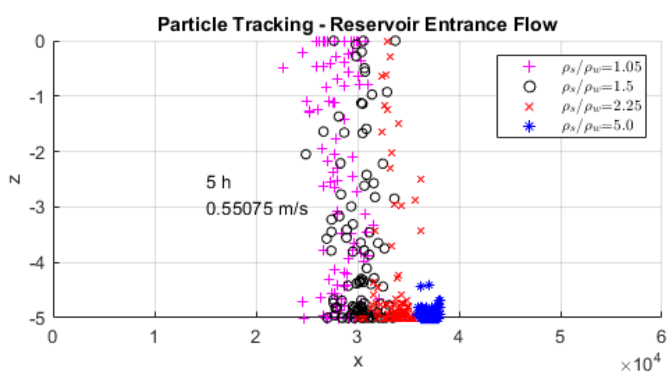

Figure 4. b

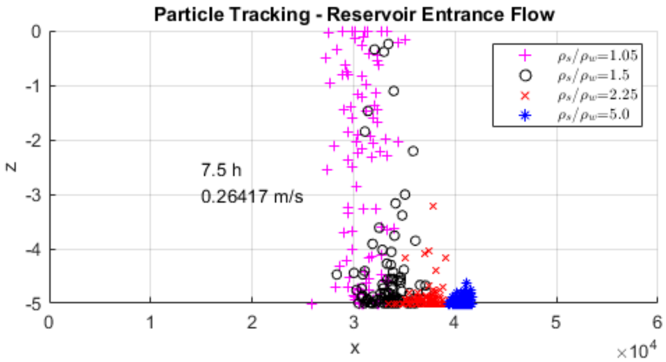

Figure 4. c

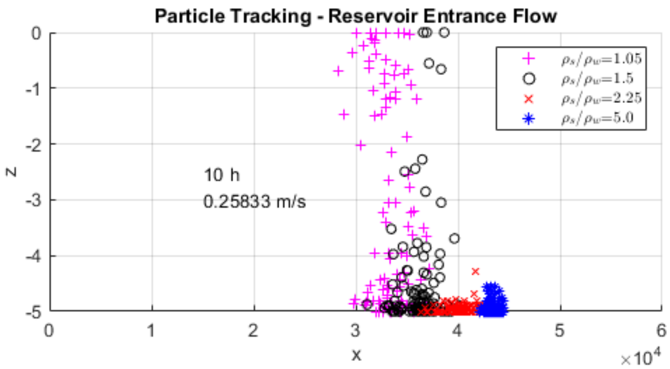

Figure 4. d

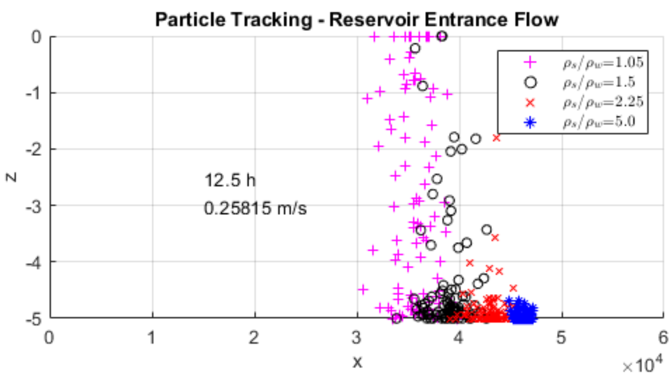

Figure 4. e

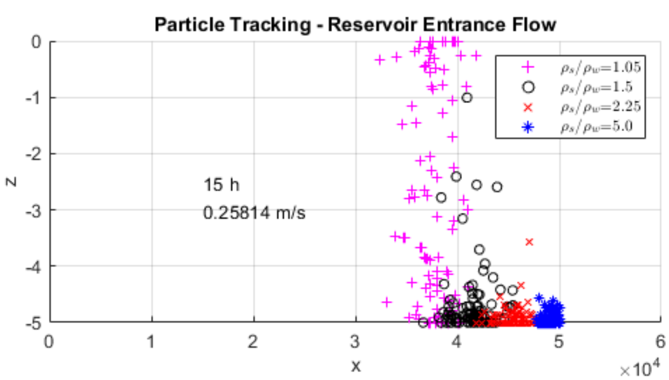

Figure 4. f

The particle tracking shows a clear dependence between settling and the density of our sediment. While all the sediment densities are mixed in a column at the beginning (Figure 4.a) following our peak velocity, the heaviest particles ($\rho_s/\rho_w = 5.0$) quickly settle during the deceleration of the flow, while the others stay suspended in the column (Figure 4.b).

Once the minimal flow velocity is reached, our sediment particles settle gradually, with the heaviest particles settling first. The exception is our lightest particles ($\rho_s/\rho_w = 1.05$) which stays well mixed in our column. While particles with $\frac{\rho_s}{\rho_w} = 2.25, 5.0$ are almost fully settled, $\frac{\rho_s}{\rho_w} = 1.5$ particles still hold some particles in the upper layers of our channel.

Another behavior is the slow down and almost stoppage of transport in the x-direction of our particles, with the heaviest ones forming a front. In real life, this equals a strong accumulation of heavy sediments at the entrance of reservoirs, while lighter sediments closer to the surface keep traveling downstream.

4.2 Concentration-Based Model

Our concentration-based model sees similar results, though its' visualization is quite different. Because the concentration-based model only looks at sediment suspended in the fluid, already deposited material does not come up in our graphs, and deposition is visualized as a decrease in concentration in our column.

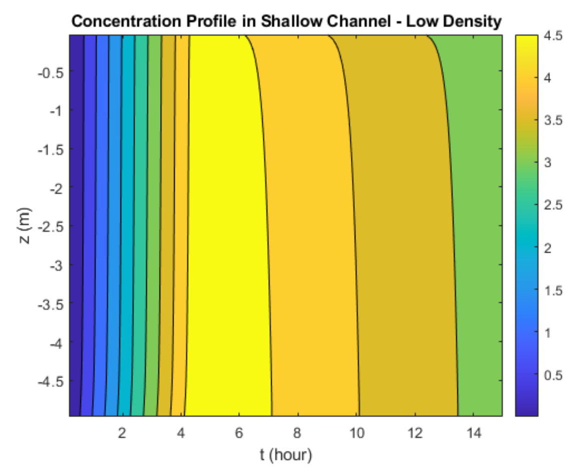

Figure 5. a H = 5m, rho ratio = 1.01

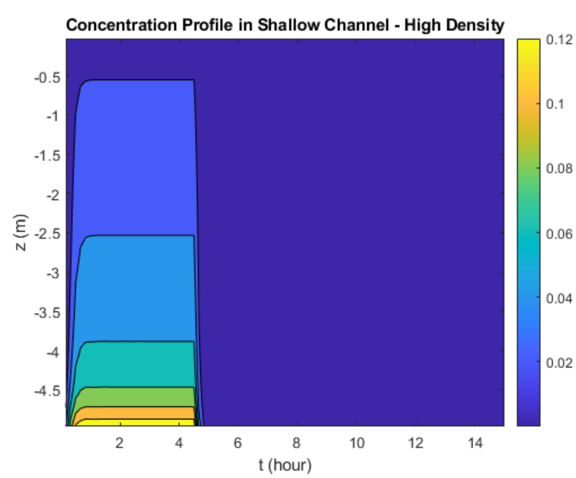

Figure 5. b H = 5m, rho ratio = 3.5

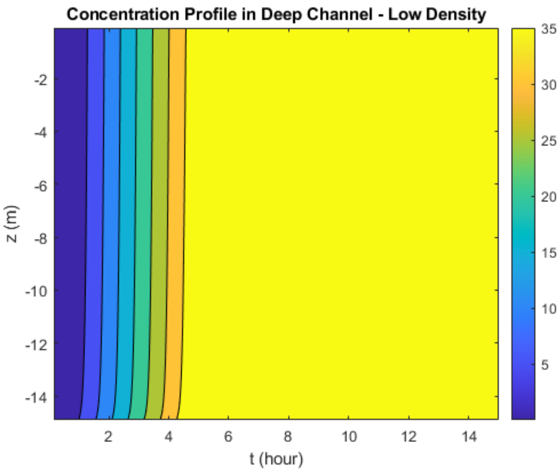

Figure 5. c H = 15m, rho ratio = 1.01

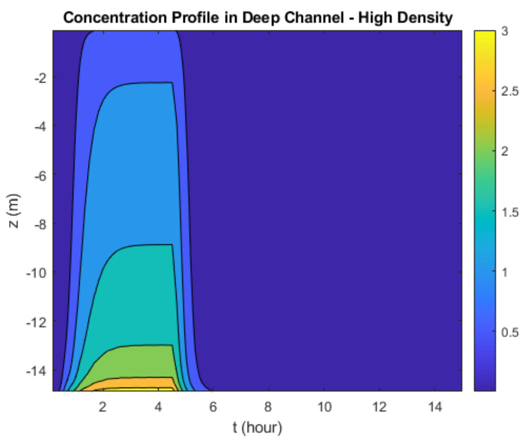

Figure 5. d H = 15m, rho ratio = 3.5

In the case of low-density sediments, we do not see a significant decrease in concentration, indicating that, like in the lower densities in our particle-based model, low-density sediments barely settle with the decreased velocity and stay afloat in the water. While the shallow channel eventually sees a slight decrease in concentration, this is nowhere to be seen in the deeper channel. This could mean that once they reach the deeper depths of a reservoir, light sediment will stay suspended and accumulate, increasing the turbidity of the reservoir water. This could lead to damage to hydroelectric turbines in a hydroelectric power plant, or significant sediment pollution downstream of the reservoir.

As for high-density sediments, we see sharp declines in concentrations in both our shallow and deep cases, (Figure 5.b and Figure 5.d) indicating quick full deposition of sediments at the decrease in flow velocity. The deposition takes longer in our deeper channel due to the higher distance for particles to travel, hence a smoother curve on our contour plot. This is also seen with higher peaks in concentration in the deeper channel where sediments have time to accumulate in the free water.

6. Conclusion

Both a particle-based model and a concentration-based model were used to look at sediment transport at the channel entrance of a reservoir experiencing decreasing velocity. As seen in both models, higher density sediments quickly decelerated and settled at the bottom of our entrance channel, while lower density stayed in suspension. This behavior of sediments in their transport in this environment could potentially create two issues. First, the deposition of heavy sediments at the entrance of the reservoir (and possibly deeper in) will modify channel characteristics and potentially reduce the reservoir's capacity over time. Second, lighter sediments staying suspended and accumulating in the reservoir could lead to increased sediment pollution downstream of the reservoir, and damage turbines if said reservoir is coupled to a hydroelectric power plant.

References

[1] Master MATLAB code provided for the 200B course. Original code from Lisa Lucas, modified by Tina Chow. Spring 2018: Mark Stacey and Michaella Chung.

[2] Modified code used for this analysis is available at: https://github.com/AlexandreSeb97/CE200B-Sp21-SedimentTransport