Environmental Hydraulics: Jets, plumes and wakes.

Sediment Management in Water Reservoirs
by Jet-Induced Density Currents

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Introduction
The management of deposited sediment in combined-sewer-overflow reservoirs is relevant both to prevent an intense bottom biochemical demand of oxygen and to maintain good water quality conditions before the water can be pumped into the water treatment plant. Many applications of sediment management, mainly related to dredging technology and depth-maintenance devices, can be found in literature ([1], [2], [3]). However, these systems are based on inertial jets rather than on buoyancy-driven flows.

Previous work on density currents ([4], [5], [6], [7], [8]) suggests that a jet-induced density current could be an effective mechanism for the transport of sediment. The conceptual idea of the model presented herein is a wall jet discharging over an erodible sloping bed. The induced flow may resuspend sediment in a way by which a self-sustained density current ignites [8]. However, this process is not always feasible since it strongly depends on the initial conditions under which the jet discharge occurs, as well as on the erosion properties of the sediment.

The purpose of the present work is to assess whether a significant amount of sediment may be resuspended by a jet and transported downward a sloping bed by a density current. The final goal of a future study is to develop a system of wall jets for the management of bottom sediment in McCook Reservoir, Chicago, Illinois.

Figure 1. Schematic of a jet-induced density current over an erodible bed. The jet discharge induces an initial sediment resuspension that may lead to the development of a self-sustaining density current.
The model
The model problem is shown in Figure 1. Therein a two-dimensional clear water jet is discharging over a movable bed with constant slope $S$. The model considers non-cohesive sediment with settling velocity $v_s$ and submerged specific gravity $R$. Future work will extend the model to the case of cohesive sediments.

The mathematical model used in this work is the four-equation, depth-averaged model presented by Parker et al. [6] with the closure relations proposed by García and Parker [5]. In this model the flow is taken to be steady and fully turbulent, and the sediment concentration is assumed to be small in order for the Boussinesq approximation to be valid.

The important layer-averaged quantities are flow velocity $U$, volumetric concentration of suspended sediment $C$, layer thickness $h$, and level of turbulence $K$ (layer-averaged value of turbulent kinetic energy). The equations governing the flow read as follows:

$$
\frac{dU h}{dx} = w_e, \quad \frac{dU^2 h}{dx} = -\frac{1}{2} R g \frac{dCh^2}{dx} + R g Ch S - u_s^2, \quad \frac{dUCh}{dx} = v_s \left( E_s - c_b \right)
$$

$$
\frac{dUKh}{dx} = u_s^2 U - \frac{1}{2} U^2 w_e - \varepsilon_0 h - R g v_s Ch - \frac{1}{2} R g w_e Ch - \frac{1}{2} R g v_s h \left( E_s - c_b \right)
$$

where $u_s$, $E_s$, $w_e$, $c_b$, and $\varepsilon_0$ are the bed shear velocity, the sediment entrainment coefficient, the water entrainment velocity, the near-bed sediment concentration, and the layer-averaged viscous dissipation, respectively. The closure relations are taken as follows:

$$
u_s^2 = \alpha K \quad (2)
$$

$$
E_s = \frac{A z_u^5}{1 + \frac{A}{0.3} z_u^5}, \quad A = 1.3 \times 10^7, \quad z_u = \frac{u_s}{v_s f \left( R_p \right)}, \quad f \left( R_p \right) = \begin{cases} R_p^{-0.6} & 3.5 \leq R_p \\ 0.586 R_p^{1.23} & R_p \leq 3.5 \end{cases} \quad (3)
$$

here $R_p = \sqrt{\frac{R g D_s D_r}{h}}$ is a Reynolds number defined using the characteristic sediment size $D_s$, the acceleration of gravity $g$, the submerged specific gravity of the sediment $R$, and the kinematic viscosity of the water $\nu$,

$$
w_e = e_w U, \quad e_w = \frac{0.075}{\left(1 + 718 R_i^{-2.4}\right)^{1/2}} \quad (4a, b)
$$

where $R_i = \frac{R g Ch}{U^2}$ is a bulk Richardson number,

$$
c_b = r_0 C, \quad r_0 = 1 + 31.5 \left( \frac{v_s}{u_s} \right)^{1.46} \quad (5a, b)
$$

and $\varepsilon_0 = \beta K^{3/2} h$, \quad $\beta = \frac{1}{2} e_w \left[ 1 - R_i - 2 \frac{C_{D*}}{\alpha} \right] + C_{D*} \quad (6a, b)$

where $C_{D*}$ is a bed friction coefficient.
This model takes into account the coupling existing between the sediment in suspension and the state of turbulence by setting the bottom shear stress proportional to the layer-averaged turbulent kinetic energy (equation 2).

**Dimensionless model equations**
The set of equations and closure relations above can be made dimensionless introducing the following dimensionless variables:

\[ x' = \frac{x}{h_0}, \quad h' = \frac{h}{h_0}, \quad U' = \frac{U}{U_0}, \quad C' = \frac{C}{C_0}, \quad K' = \frac{K}{K_0}, \quad \epsilon'_0 = \frac{\epsilon_0}{\epsilon'_0}, \quad E'_s = \frac{E_s}{C_0}. \]

The dimensionless equations then read:

\[
\frac{dU'}{dx'} = e'_w U', \quad \frac{dU'^2 h'}{dx'} = -\frac{1}{2} R_{i0} \frac{dC'h^2}{dx'} + S R_{i0} C'h' - \alpha \frac{K}{U_0^2}, \quad \frac{dU'K'h'}{dx'} = \alpha K'U' + \frac{1}{2} U_0^2 \epsilon'_0 - \left( \frac{U_0^2}{K_0} \right)^{1/2} \epsilon'_0 h' - \frac{1}{2} R_{i0} \frac{U_0^2}{K_0} \frac{v_s}{U_0} C'h' - \frac{1}{2} R_{i0} \frac{U_0^2}{K_0} \frac{v_s}{U_0} h'(E'_s - r_0 C') \quad (7a, b, c, d)
\]

From the analysis of the equations and closure relations it can be seen that the dimensionless parameters governing the flow are \( R_{i0} = \frac{R g C_0 h_0}{U_0^2 v_s}, \quad \frac{U_0}{v_s}, \quad \alpha, \quad S, \quad \frac{U_0^2}{K_0}, \quad C_D^* \) and \( R_p, \quad U_0, \quad h_0 \) and \( K_0 \) are the initial values, and \( C_0 \) is computed from equations (1c), (5a) and (5b) at equilibrium, i.e. as that value which gives zero net erosion. The initial value for \( K_0 \) is set to \( C_D^* U_0^2 / \alpha \), in such case \( U_0^2 / K_0 = \alpha / C_D^* \).

**Regime analysis**
The model problem described above was analyzed numerically solving the set of equations (1a)-(1d). Solutions for \( R_p = 0.783, \quad S = 0.02, \quad C_D^* = 0.01, \quad \alpha = 0.1 \), were computed in order to determine the flow regime for different initial conditions, represented by the dimensionless numbers \( R_{i0} \) and \( U_0 / v_s \).

A clear-water jet discharging over a movable bed induces highly erosive flow conditions. The suspended sediment produces a lower layer of denser-fluid that becomes the driving force for the underflow to develop, and at the same time is a source of turbulence. However, the sediment is kept in suspension if the state of turbulence is high enough, being the work needed to keep sediment in suspension a sink of turbulent kinetic energy. This competitive process may or may not lead to a self-sustained flow, which is fully governed by the initial conditions of the jet as well as the characteristics of the sediment being resuspended.

Figure 2 presents three different regions, each region corresponding to values of jet discharges that lead to flows with different characteristics. Region below curve A (region I) is characterized...
by jets with low inertia which do not induce enough sediment resuspension to ignite a self-sustaining process. After an initial adjustment length, the density current starts to deposit the sediment in suspension, and eventually, the sediment flux $\psi$ ($\psi = UCh$) and $U$ vanish. The density current behaves as a jet-like flow. Solutions in figures 3 and 4 for $U_0/v_s = 400$ and 500 are typical of these flows. For jet discharges near curve A, the flow reaches a pseudo equilibrium. After an initial adjustment length resuspension balances deposition, and $\psi$ as well as $U$ reach approximately constant values. This behavior of the solution can be observed in Figures 3 and 4 (solutions for $U_0/v_s = 555$).

Jet discharges corresponding to region between curves A and B (region II) induce a self-sustained process leading to the development of downslope flowing density currents. As $U_0/v_s$ increases in this region the density current accelerates faster and induces higher sediment resuspension. Curves for $U_0/v_s > 555$ in Figure 3 and 4 are typical of this behavior.

When a density current is started with a jet discharge in the region above curve B (region III), it eventually becomes sub-critical and dies out. The evolution of subcritical flows has not been fully investigated yet.

Figure 5 presents the dimensionless local sediment resuspension $(d\psi/dx/(U_0C_0))$ for $Ri_0=2$ and several values of $U_0/v_s$, a positive value indicates resuspension and a negative value indicates deposition. Figure 5 also shows that for every flow regime there is high sediment entrainment at the very beginning, $x' < 50$. The higher deposition (flows related to region I) or smaller resuspension (flows related to region II) occurs at a distance $x'$ between 80 and 110. It should be noted that the high sediment entrainment at the very beginning may deplete the initial portion of sediment bed preventing the ignition of the density current.

Conclusions
The present work predicts the possibility of generating self-sustaining density currents capable of transporting significant amount of sediment with the help of wall jets. These results are currently being used to design a system for the management of bottom sediment in McCook reservoir, Chicago, Illinois.

Jet-induced density currents may become a passive mechanism for the managing of bottom sediment with almost no maintenance needed, which makes it an attractive tool considering that such system would be used only after extreme hydrologic events capable of producing combined sewer overflows.

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References

**Figure 2.** Curves A and B delimit three regions, each one corresponding to values of jet discharges that lead to flows with different characteristics.

**Figure 3.** Dimensionless velocity for Ri₀ = 2. Solutions for U₀/Vₛ = 555 correspond to jet discharges over curve A, solutions for U₀/Vₛ < 555 correspond to jet discharges in region I, and solutions for U₀/Vₛ > 555 correspond to jet discharges in region II.
Figure 4. Dimensionless sediment flux for $Ri_0 = 2$. Solutions for $U_0/v_s = 555$ correspond to jet discharges over curve A, solutions for $U_0/v_s < 555$ correspond to jet discharges in region I, and solutions for $U_0/v_s > 555$ correspond to jet discharges in region II.

Figure 5. Dimensionless local sediment resuspension for $Ri_0 = 2$. Solutions for $U_0/v_s = 555$ correspond to jet discharges over curve A, solutions for $U_0/v_s < 555$ correspond to jet discharges in region I, and solutions for $U_0/v_s > 555$ correspond to jet discharges in region II.