Connecting Hyperpycnal Flow Deposits to River Flood Dynamics*

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Abstract

Hyperpycnal flows are turbid river plumes that can plunge to form turbidity currents where they enter a water body of lesser density. Because these flows provide one of the most direct connections between terrestrial sediment sources and marine depositional sinks, their deposits preserve an important record across a variety of climatic and tectonic settings. A leading hypothesis assumes that hyperpycnal-flow velocity scales directly with river discharge, such that individual turbidites record the rising and falling discharge of a flooding river. Using a 1D numerical model and flume experiments, we test this hypothesis and find that turbid river flow must move through a backwater zone, depth-limited plume, and plunging zone before becoming a turbidity current. These zones can extend tens of kilometers offshore and significantly affect the transfer of momentum from river to turbidity current. Counter to the proposed hypothesis, our results indicate that local flow velocities within hyperpycnal flows can be uncorrelated or even anti-correlated with inlet river discharge because of translation of the plunge point resulting from temporal variations in discharge and sediment concentration through the course of a river flood. Furthermore, hyperpycnal flow deposits can be influenced by both local plunge-point dynamics and inlet river conditions, and the relative degree of influence depends on the advection length scale of settling sediment. Results also suggest that the criteria used to identify plunging hyperpycnal flows (a flow density in excess of the ambient fluid) is a necessary, but not sufficient condition. The basin also must be deep enough, in cases greater than tens of meters, in order for the plume to collapse and form a turbidity current.
References


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Plunging hyperpycnal river plumes

Current Ideas:

1. River plumes plunge when denser than seawater

2. Depositional record of river floods (river response to climate change)

3. Deposits track the hydrograph of a flooding river

River Reuss, Switzerland, 2005

Mulder and Alexander, 2001
Do hyperpycnal-flow deposits record river flood dynamics?

Slump-generated vs. Hyperpycnal river plume

- Deposition under decelerating flow
- Reverse to normal grading (after Mulder and Alexander, 2001)

- Deposition following river hydrograph
Zones of flow: Hyperpycncal Plume
Zones of flow: Hyperpycnal Plume

- Backwater Zone
- Normal Flow Zone
- Depth-limited Zone
- Plunging Zone
- Turbidity Current Zone
Numerical Formulation

1. 1D Layer averaged equations of motion (St. Venant)
2. Conservation of fluid mass and momentum
3. No erosion or deposition
4. Upstream of shoreline: backwater equation

\[ \frac{dh}{dx} = \frac{S_b - C_f F^2}{1 - F^2} \]
1. 1D Layer averaged equations of motion (St. Venant)
2. Conservation of fluid mass and momentum
3. No erosion or deposition
4. Upstream of shoreline: backwater equation
   \[ \frac{dh}{dx} = \frac{S_b - C_f F^2}{1 - F^2} \]
5. Plunge zone: \( F_{dp} = 0.5 \) at plunge point (Akiyama and Stefan, 1984; Toniolo and Parker, 2007)
   \[ h_p = \left( \frac{q_p^2}{(\Delta \rho / \rho_a) g F_{dp}^2} \right)^{1/3} \]
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5. Plunge zone: $F_{dp} = 0.5$ at plunge point (Akiyama and Stefan, 1984; Toniolo and Parker, 2007)

6. Turbidity current zone: steady and uniform

$$h_p = \left( \frac{q_p^2}{(\Delta \rho / \rho_a) g F_{dp}^2} \right)^{1/3}$$
Example case: Huanghe River, China

[Graph A] Elevation above sea level (m)

[Graph B] Velocity (m/s)

T1: $q_0 = 4 \text{ m}^2/\text{s}, c_0 = 1.7\%$
Source to sink signal transfer

Plunge point

Velocity reversal
Source to sink signal transfer

Input: Flood Acceleration

Mixed pulsing and deceleration signal in plunging zone

Muted acceleration signal in turbidity current

Lamb and Mohrig, 2009, Geology
2-D experimental facility

Sediment + Water

Test section (2.5 m)

Stand pipe

Head box

NOT TO SCALE

β

~0.135 m

Vent Drain

Depth-limited plume

Plunge point

Turbidity current

0.1 m

Lamb et al., in press, GSAB
Flume Results

• Increasing discharge results in seaward movement of the plunge point.

• Local velocity is anti-correlated with discharge in plunge zone.

• Despite complex local flow dynamics, deposition rate is most sensitive to inlet discharge.

Lamb et al., in press, GSAB
Advection length scale

\[ l_a = \frac{UH}{r_0 W_s} \]

= Flow Velocity x settling time
Advection length scale

Flow velocity

Settling Velocity

Advection length

If plunge point translation > \( l_a \)

Deposition governed by divergence in local transport capacity. Deposits record local plunge point dynamics.

\[ q_s = q_{sc} \]

\[ l_a = \frac{UH}{r_0 W_s} \]

= Flow Velocity x settling time
Advection length scale

If plunge point translation $> l_a$

Deposition governed by divergence in local transport capacity. Deposits record local plunge point dynamics.

$q_s = q_{sc}$

If plunge point translation $< l_a$

Settling sediment cannot respond to local flow. Deposition governed by inlet boundary conditions. Deposits record river flood dynamics.

$q_s = q_{s0}$

$\frac{UH}{r_0 W_s} = \text{Flow Velocity} \times \text{settling time}$
Example calculations of advection length scale

\[ l_a = \frac{UH}{r_0 w_s} \]

<table>
<thead>
<tr>
<th></th>
<th>( q ) (m(^2)/s)</th>
<th>( w_s ) (m/s)</th>
<th>( l_a )</th>
<th>Plunge point translation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Laboratory</strong></td>
<td>1 to 4 ( \times 10^{-3} )</td>
<td>4.4 ( \times 10^{-4} )</td>
<td>1.5 to 6 m</td>
<td>0.5 m</td>
</tr>
<tr>
<td><strong>Field (silt)</strong></td>
<td>5 to 20</td>
<td>4.4 ( \times 10^{-4} )</td>
<td>7.5 to 30 km</td>
<td>10 s km</td>
</tr>
<tr>
<td><strong>Field (sand)</strong></td>
<td>5 to 20</td>
<td>9 ( \times 10^{-3} )</td>
<td>0.3 to 1.2 km</td>
<td>10 s km</td>
</tr>
</tbody>
</table>

Sand is likely to record plunge point dynamics (not river flood discharge) at field scale

Lamb et al., in press, GSAB
Conclusion 1: Flow Dynamics

Hyperpycnal plume *velocities* do not linearly follow the flood discharge curve.

Depth-limited and plunging zones: anticorrelations, uncorrelations, and multiple accelerations and decelerations are possible due to the movement of the plunge point.
Conclusion 2: Depositional signature

Despite complex spatial changes in flow, plume deposits might still record inlet discharge and sediment concentration depending on the advection length scale.

**Low discharges and coarse sediment:**

\[ l_a \rightarrow 0 \]

Deposits record local dynamics (plunge point translation – multiple pulses)

**High discharges and fine sediment:**

\[ l_a \rightarrow \infty \]

Deposits record inlet conditions (fluvial discharge and sediment concentration)
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