Plunging Liquid Jet Reactors for Dilution and Aeration of Brine Discharges

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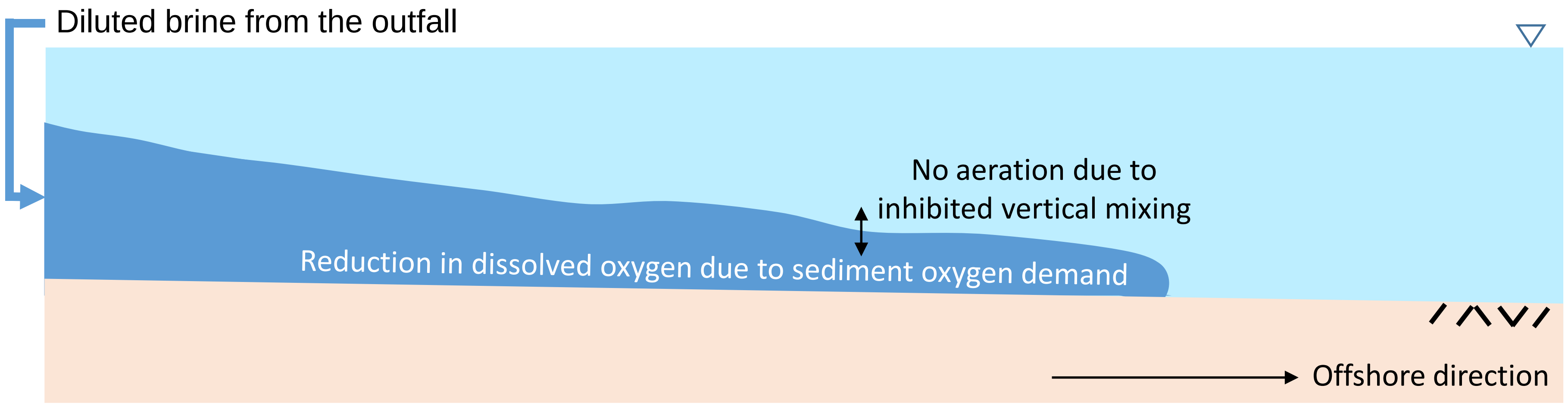
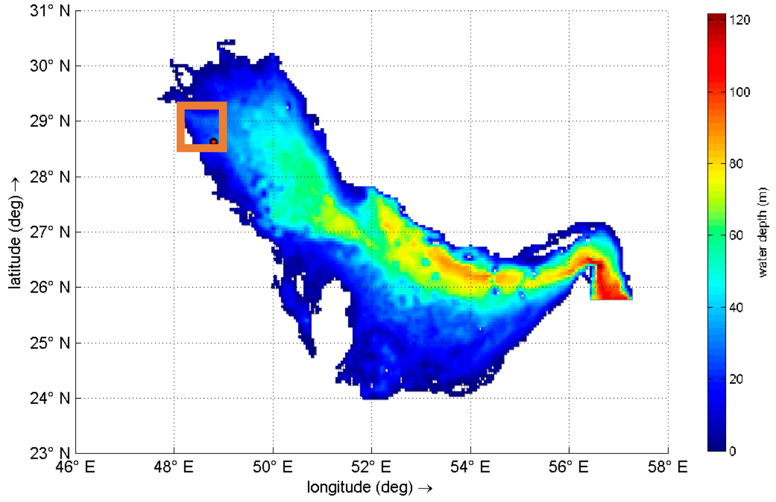
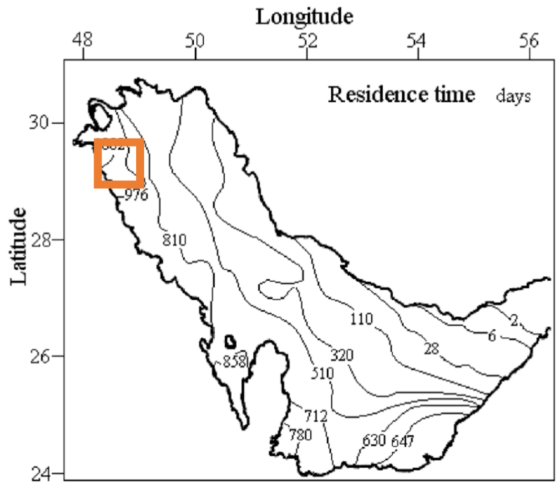
Seawater desalination

- Important source of freshwater for many parts of the world.
- Two main processes for desalination:
  - Multistage flash (MSF)
  - Reverse osmosis (RO)
- With a 50% recovery ratio, produced brine has twice the salinity of seawater (excess salinity of about 40 psu).
- A total dilution of 20 is required to dilute brine to an excess salinity of 2 psu.

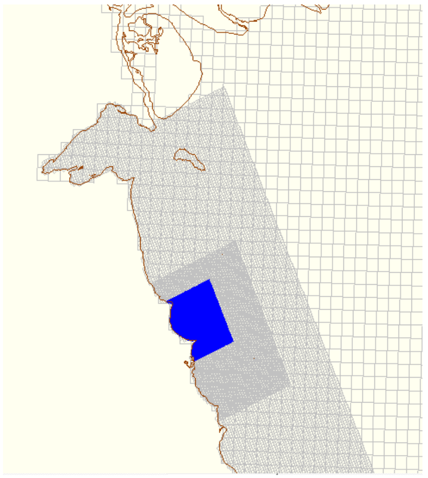


Total Dilution
(application to Arabian Gulf Al-Zour)

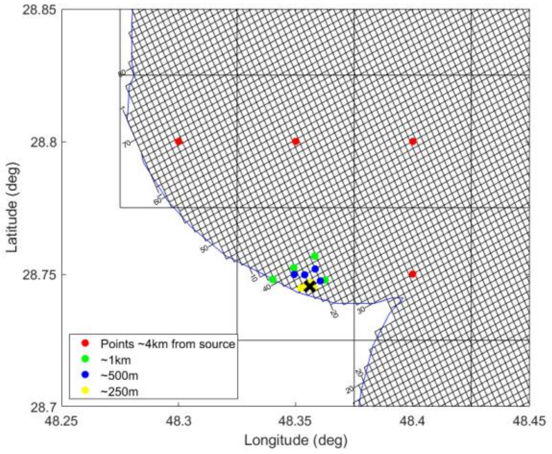




Alosairi et al., *JGR* 2011



DELFT3D with nesting



Chow et al., *Water* 2021
(DELFT3D)

$$S_{F,h} = \frac{n}{\sum_n \frac{1}{Si}}$$

$S_{F,h} = 28$, $S_N = 20$, $S_T = 12$

$S_{F,h} = 28$, $S_N = 70$, $S_T = 20$

Total Dilution
(combining near and far field dilutions)

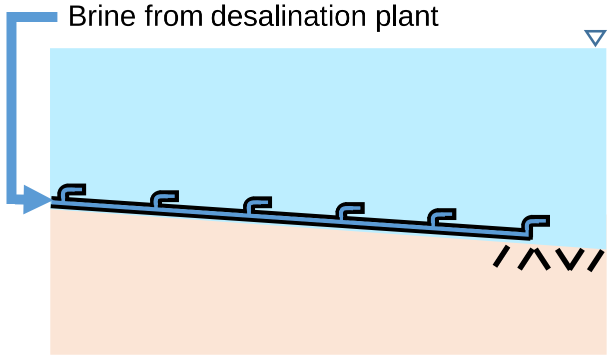
$$S_F = \frac{(co - ca)}{(cF - ca)}$$

$$S_N = \frac{(co - cF)}{(cN - cF)}$$

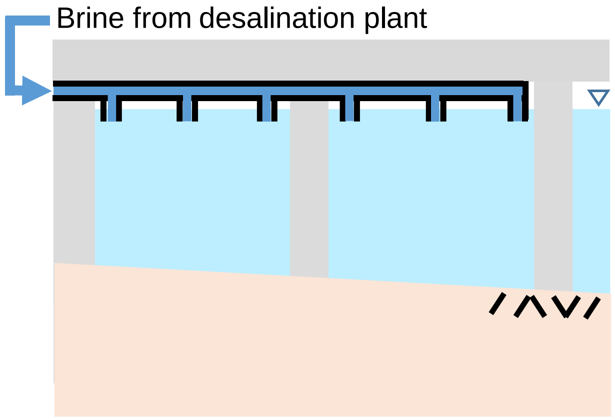
$$S_T = \frac{(co - ca)}{(cN - ca)}$$

$$\frac{1}{S_T} = \frac{1}{S_F} + \frac{1}{S_N} - \frac{1}{S_N S_F} \cong \frac{1}{S_F} + \frac{1}{S_N}$$

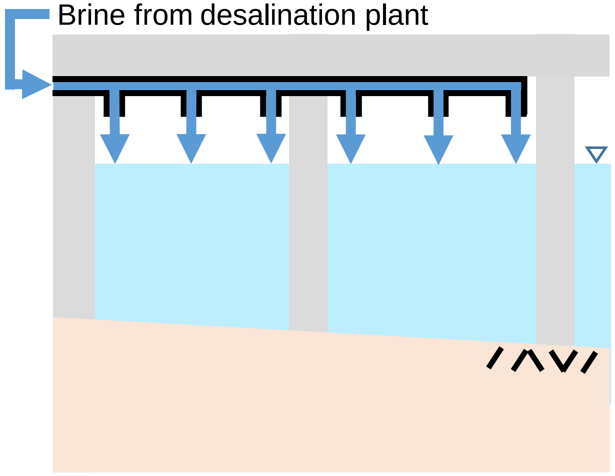
Options for brine disposal



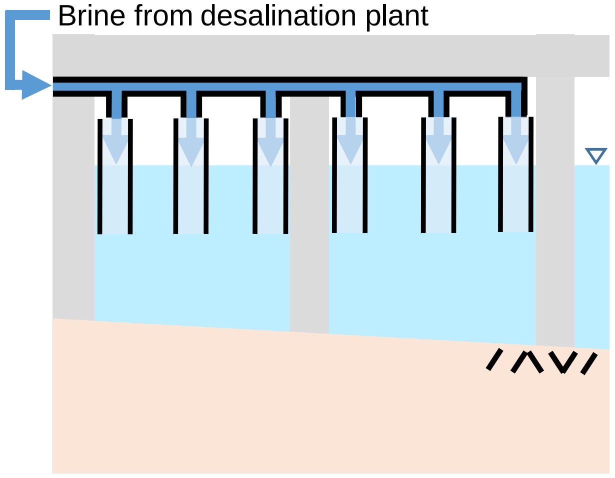
Option 1: Submerged diffuser



Option 2: Surface plume



Option 3: Unconfined plunging jet



Option 4: Confined plunging jet

Options 3 and 4 provide aeration of the water column, but do they provide enough mixing?

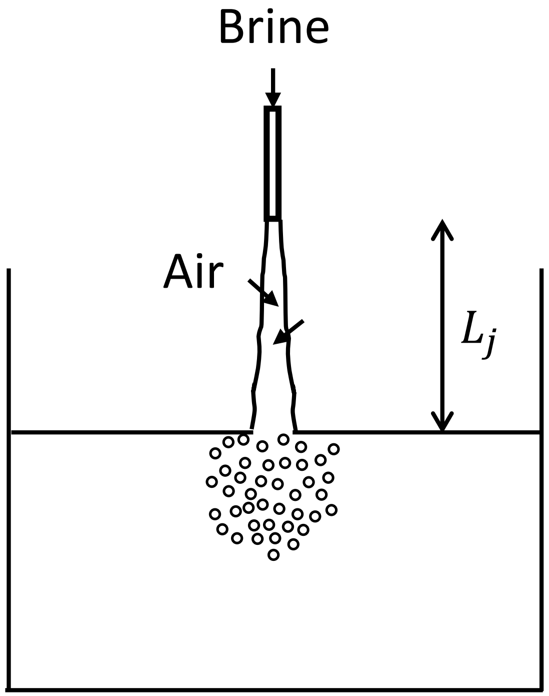
Oxygen Efficiency

Aerator Type		OE (kg O_2/kWh)
Diffused Air [26]	Fine bubble	1.2–2.0
	Coarse bubble	0.6–1.2
	Submerged jet	1.2–2.4
	Deep shaft [28]	3.0–6.0
	Static mixer [29]	1.2–1.8
Pure Oxygen [26]	UNOX	2.4–3.8
	VITOX	2.8–4.2
Mechanical [26]	Simcar surface aerator	2.1–2.4
	Turbine aerator	2.1–3.2
	Simple cone	2.0–2.6
Oxidation brushes [26]	Kessener brush	2.4–3.2
	Cage rotor	1.4–3.0
Plunging jet (air–water) [27]	Unconfined systems	0.7–8.0
	Confined systems	0.3–4.0
	Bioreactor [30]	2.0–4.6

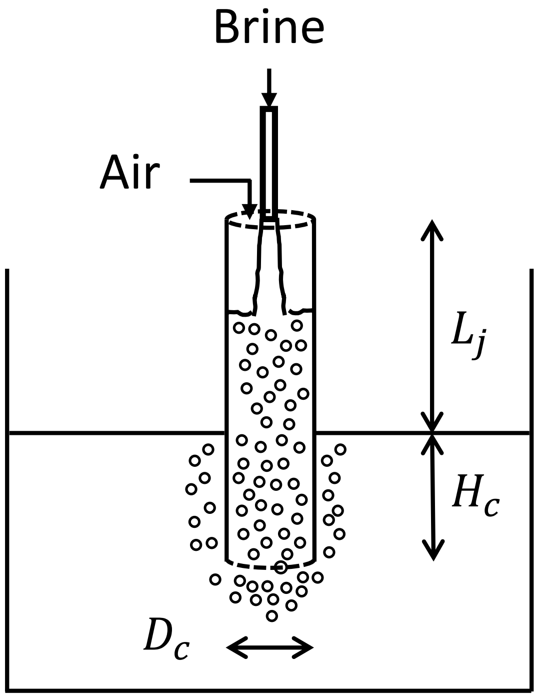
Chow et al., Processes 2020

Plunging jets

- High velocity jets that entrain air before impingement on the surface of receiving water.
- Momentum of the jet and negative buoyancy help push the air bubbles down.
- Momentum and buoyancy also help in generating mixing.



Unconfined

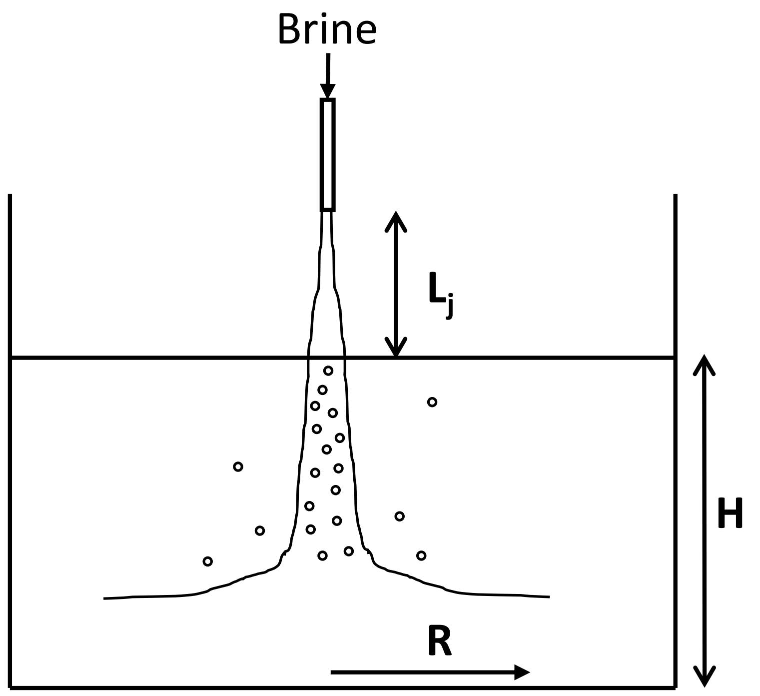


Confined

Experiments

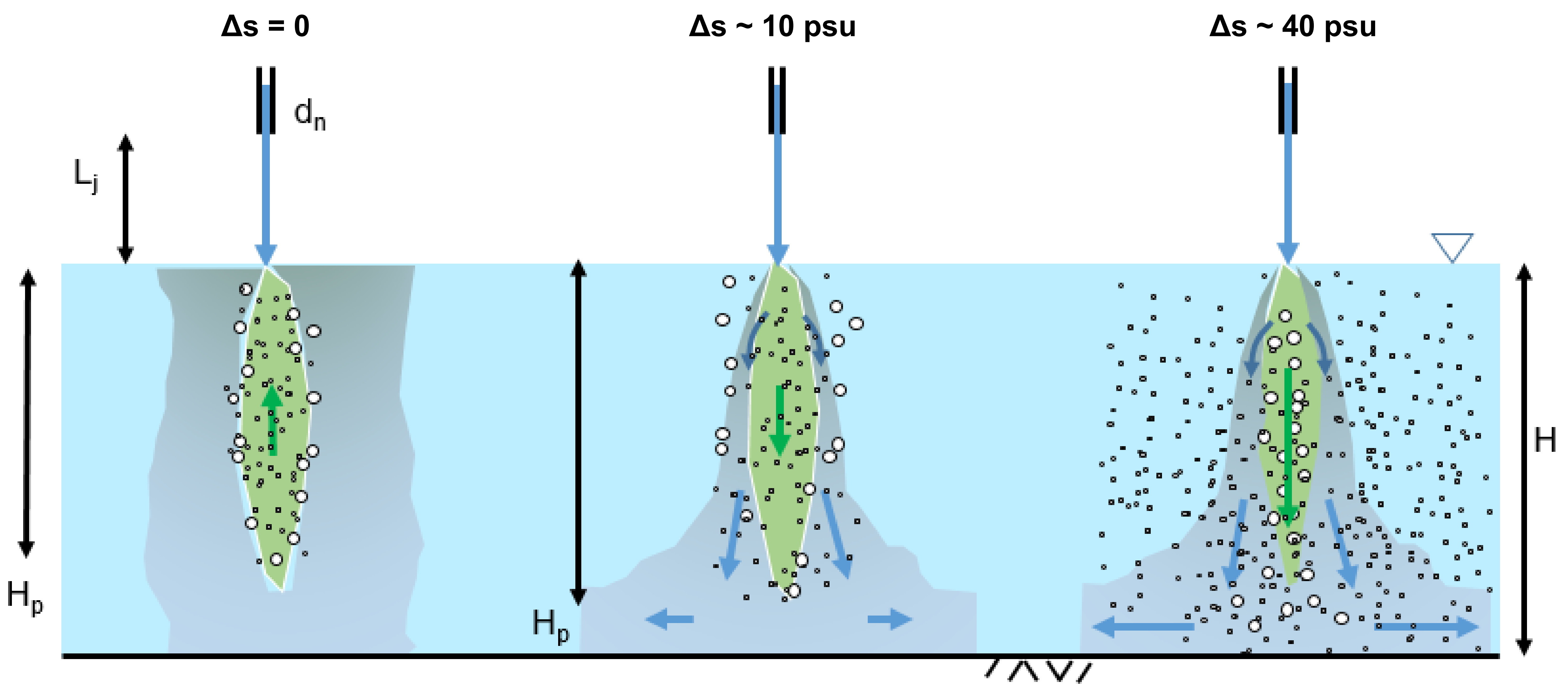
- Laboratory experiments designed to model one jet in an array of 6 plunging jets discharging 1 m^3/s of brine in a depth of 8 m.
- Experimental parameters scaled using Froude scaling with a length ratio of 16:1 (field:lab).

Parameters	Experiment	Scaled to the field
Nozzle diameter, d_n (cm)	1	16
Jet length, L_j (cm)	0 - 60	0 – 960
Water depth, H (cm)	50	800
Flow rate, Q_b (cm^3/s)	160	163840
Measurement distance, R (cm)	50	800
Salinity difference, Δs (psu)	10, 40	10, 40

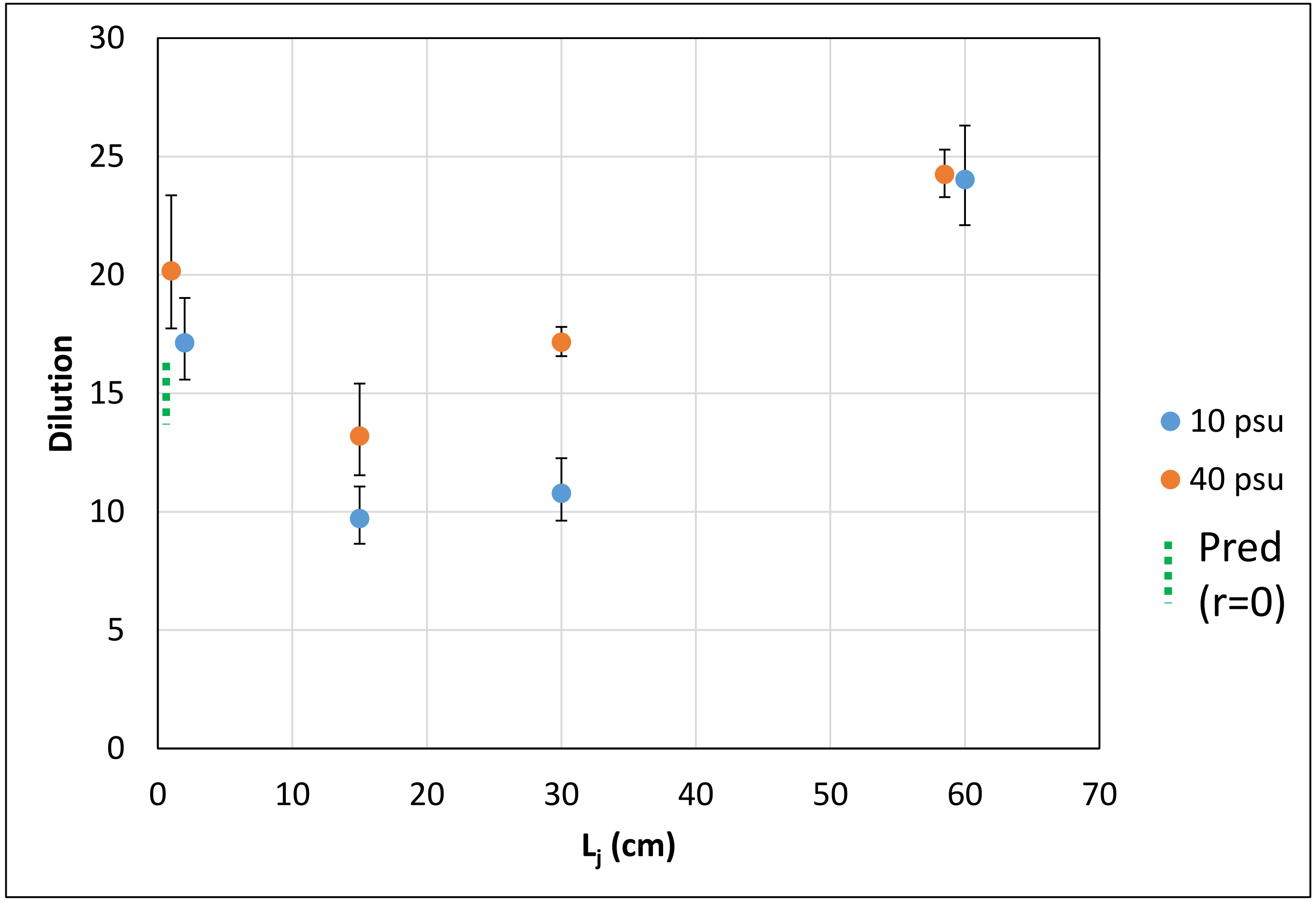


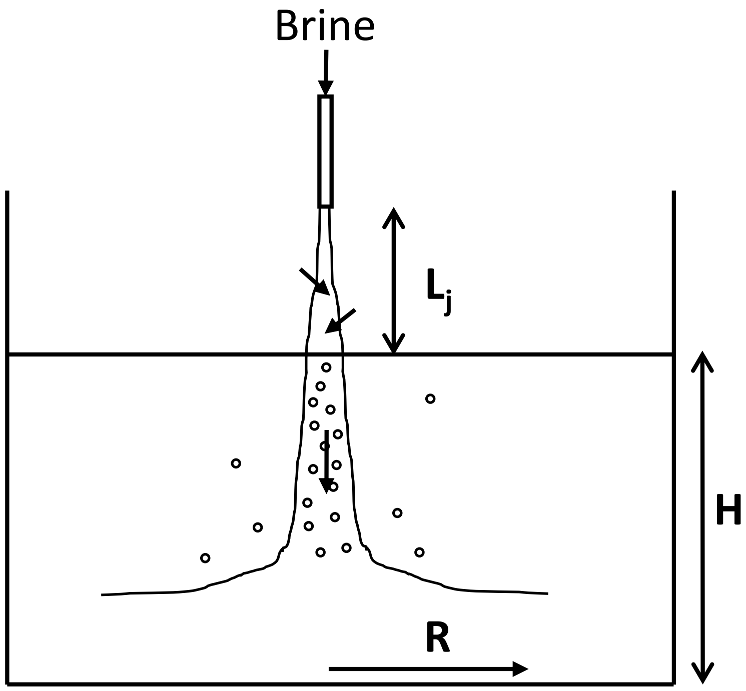
- Fluorescent dye added to brine and concentrations measured using a fluorometer to calculate dilution.

Schematic - Unconfined plunging jet observations



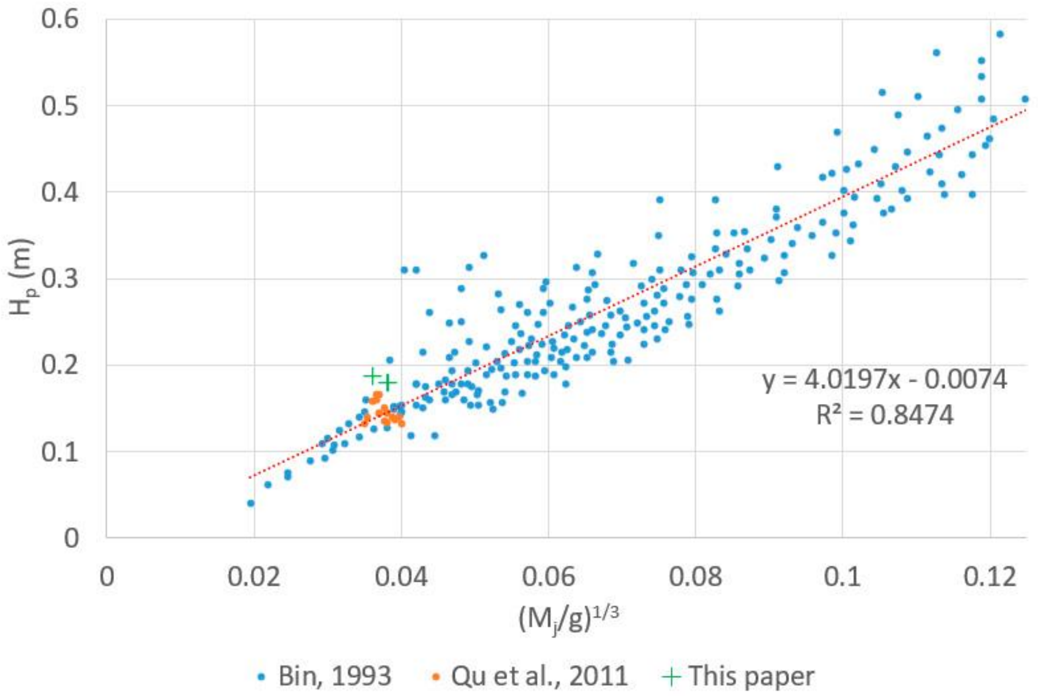
Unconfined jets: effect of jet length on dilution



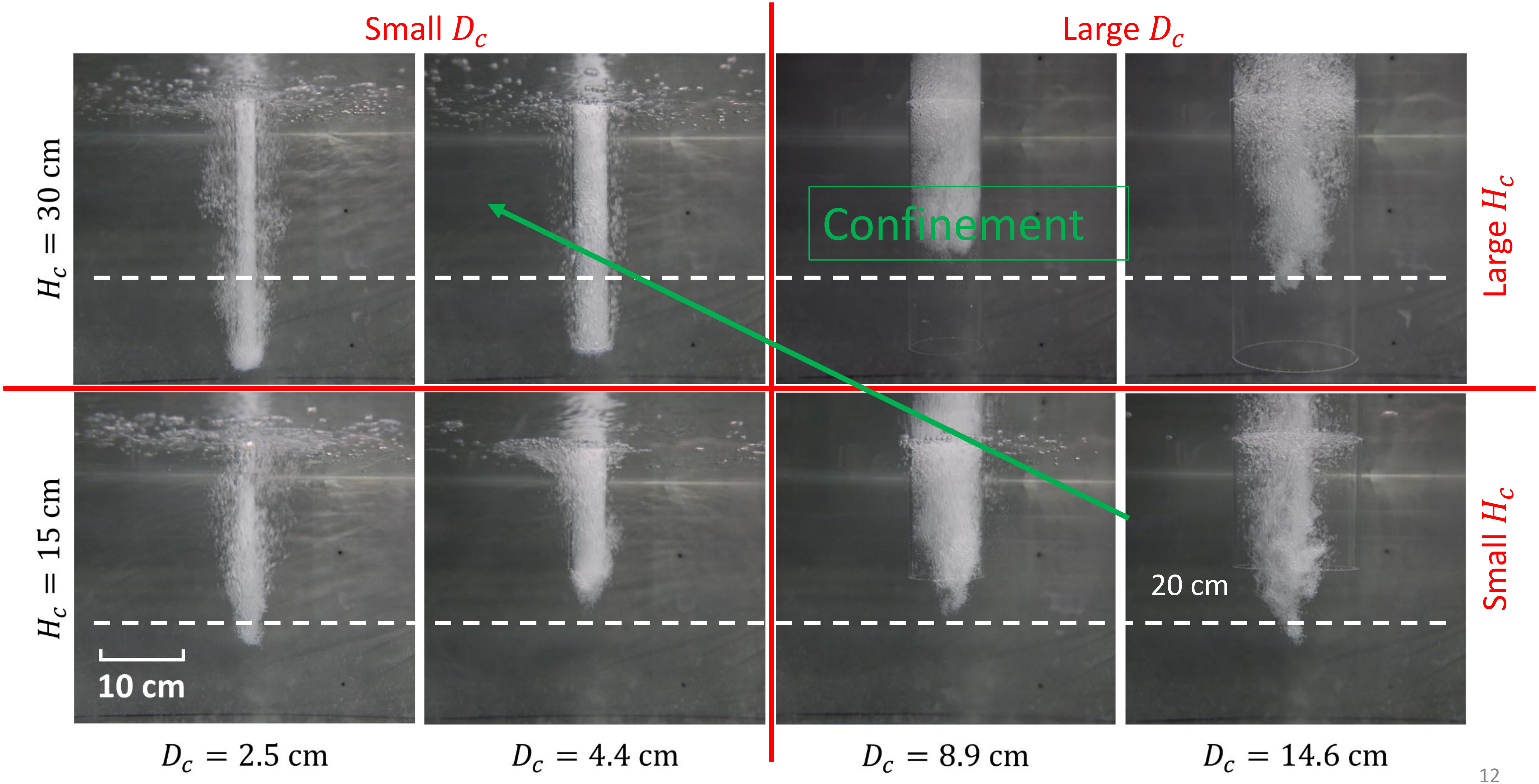


- Non-monotonic behavior wrt L_j
- Results for L_j = 0 comparable to initial mixing theory
- Some improvement with denser effluent

Bubble Penetration Depth

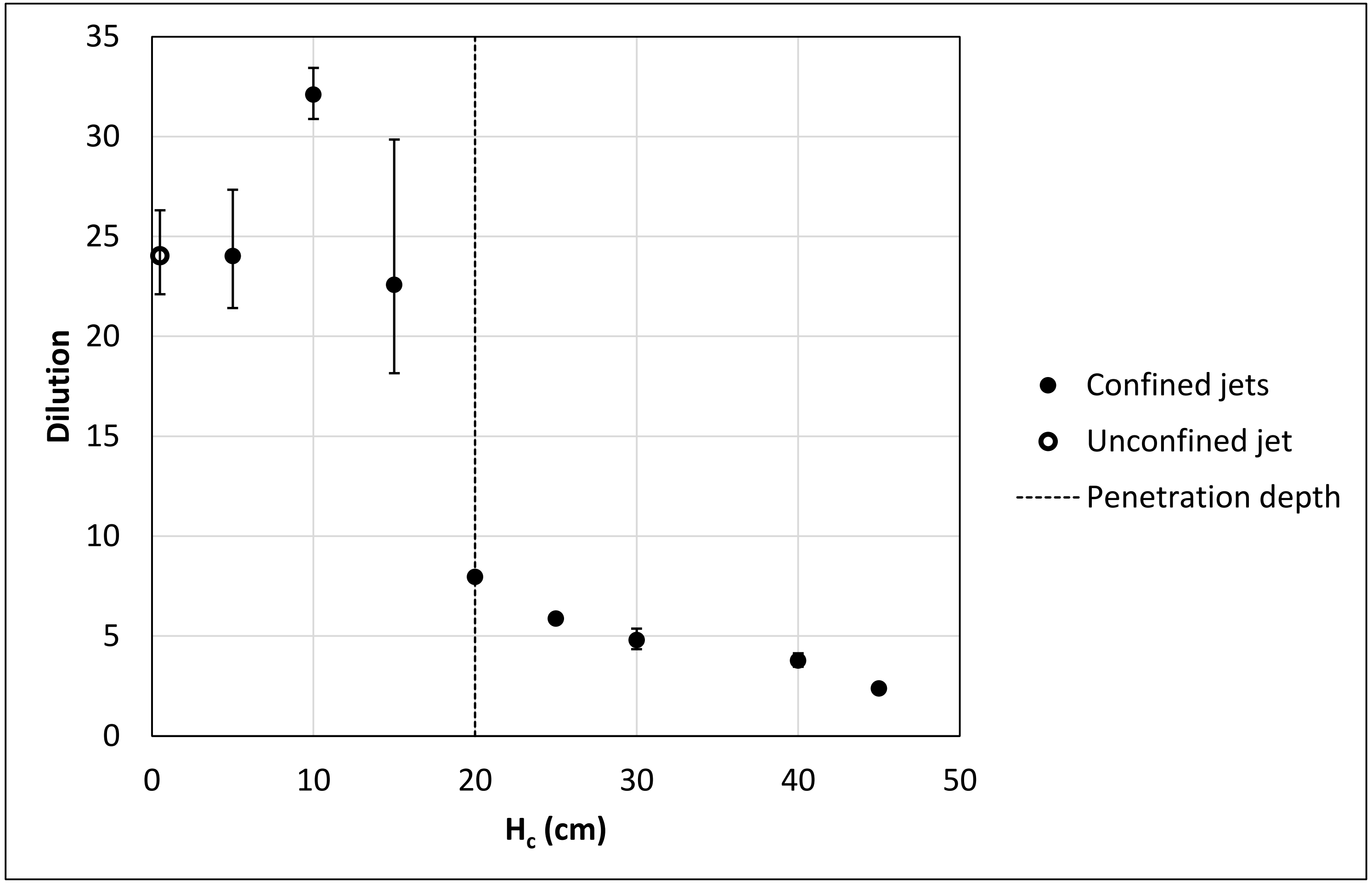


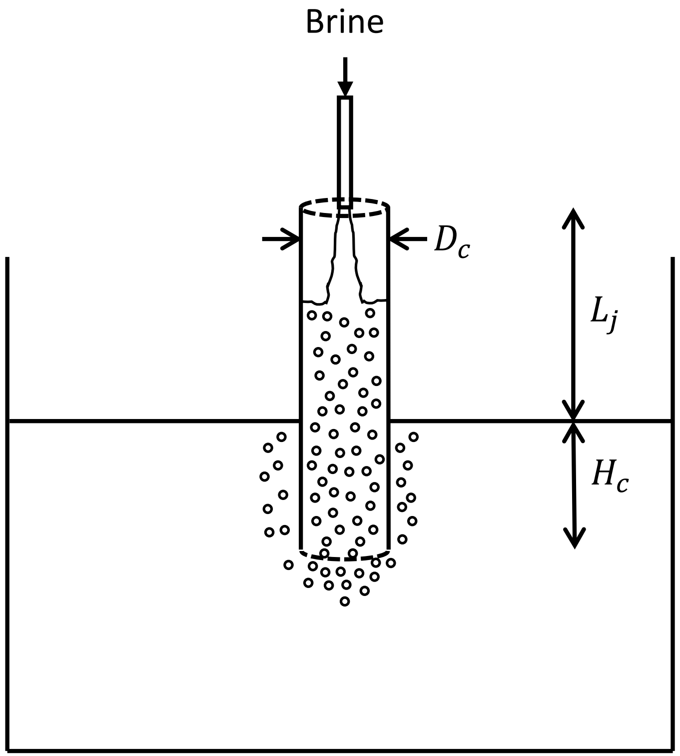
Confined jet: bubble penetration depth



Confined jets: effect of downcomer depth on dilution

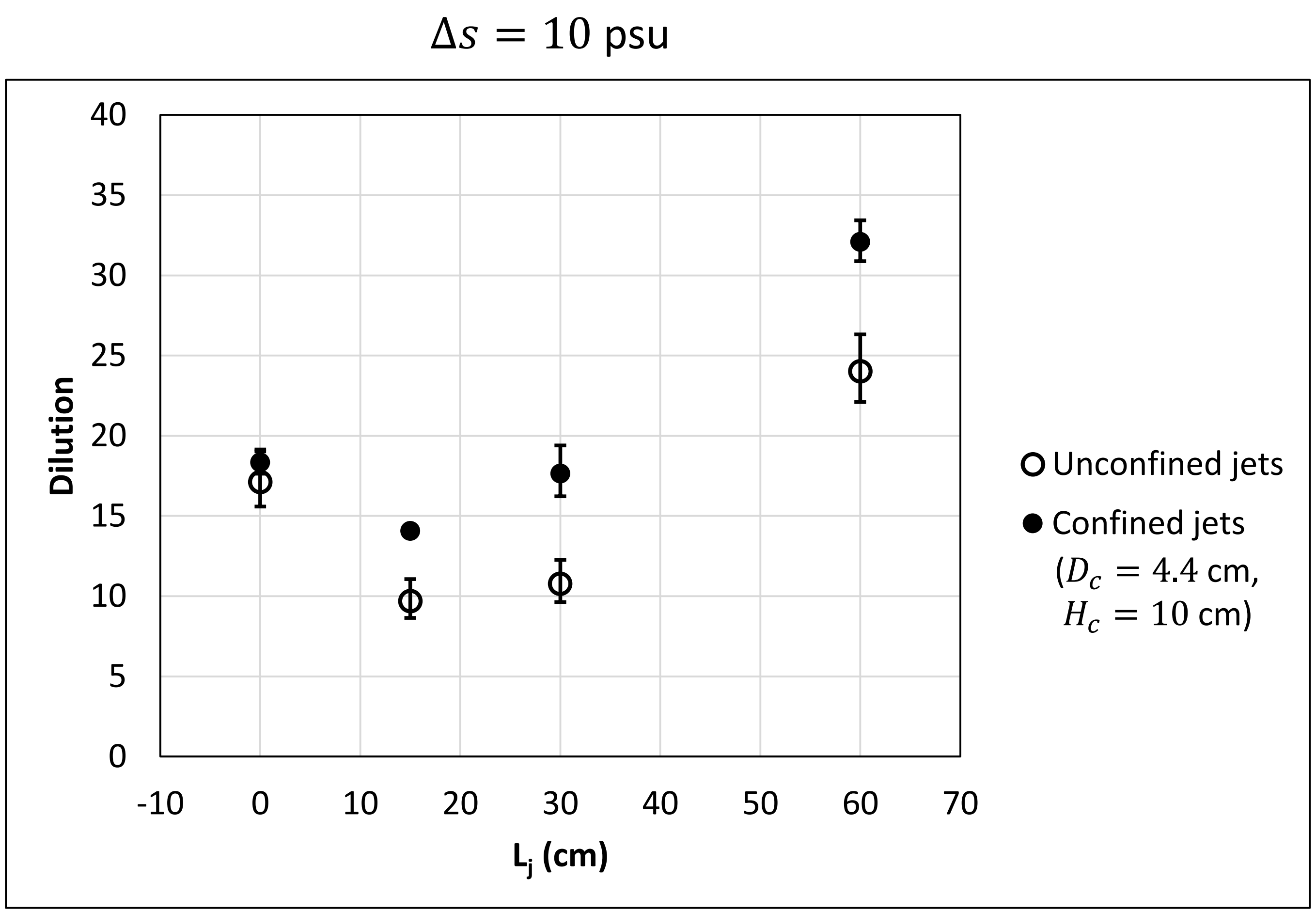
$L_j = 60$ cm, $D_c = 4.4$ cm, $\Delta s = 10$ psu

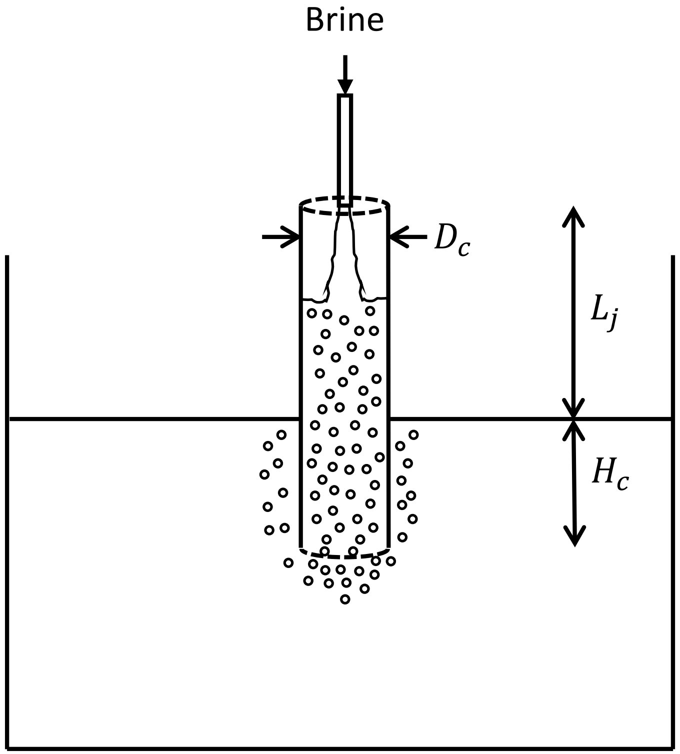




- Comparable to unconfined for $H_c < H_p$ except $H_c = 10$.
- Strong drop off for $H_c > H_p$

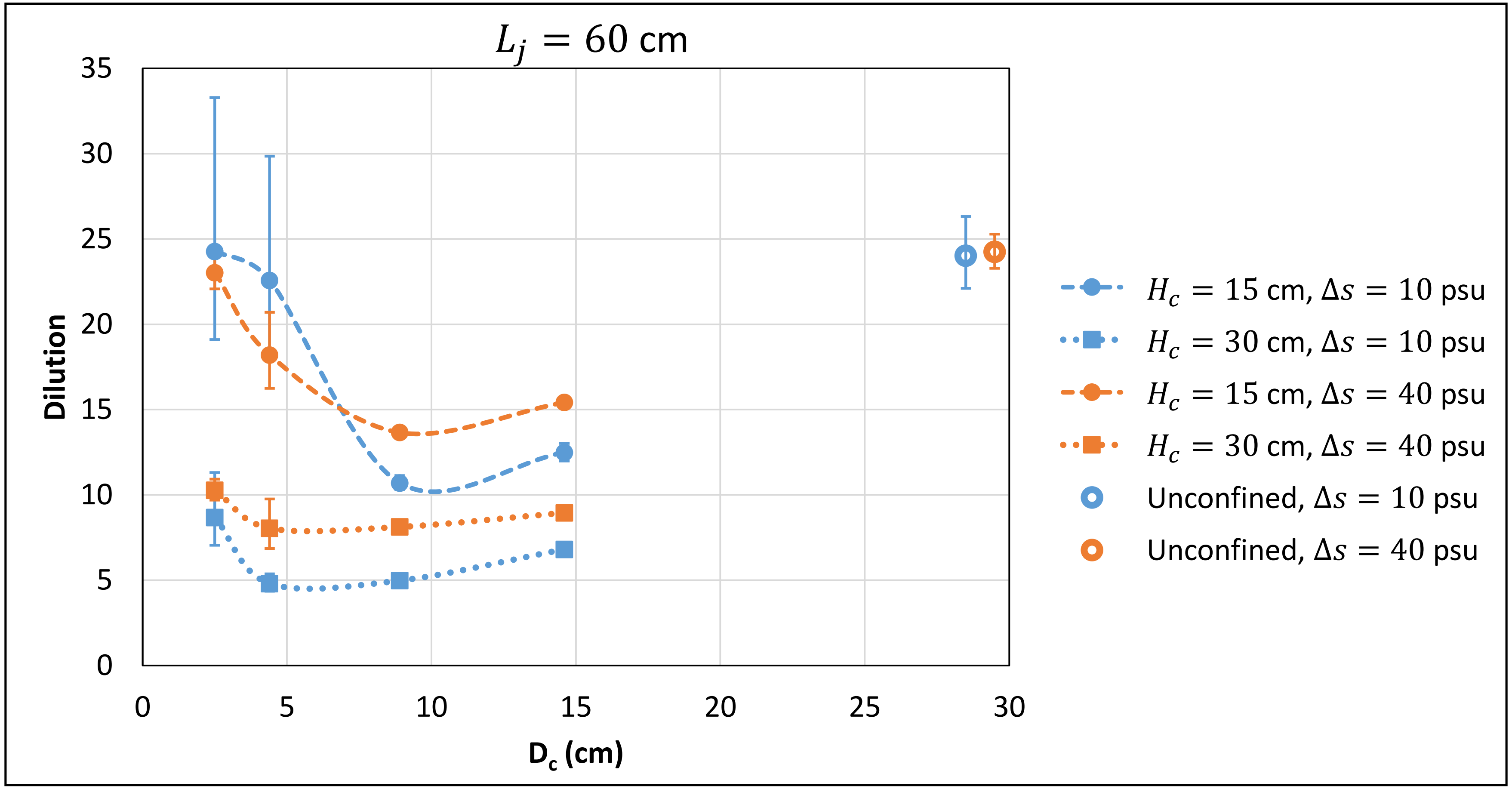
Confined jets: effect of jet length on dilution

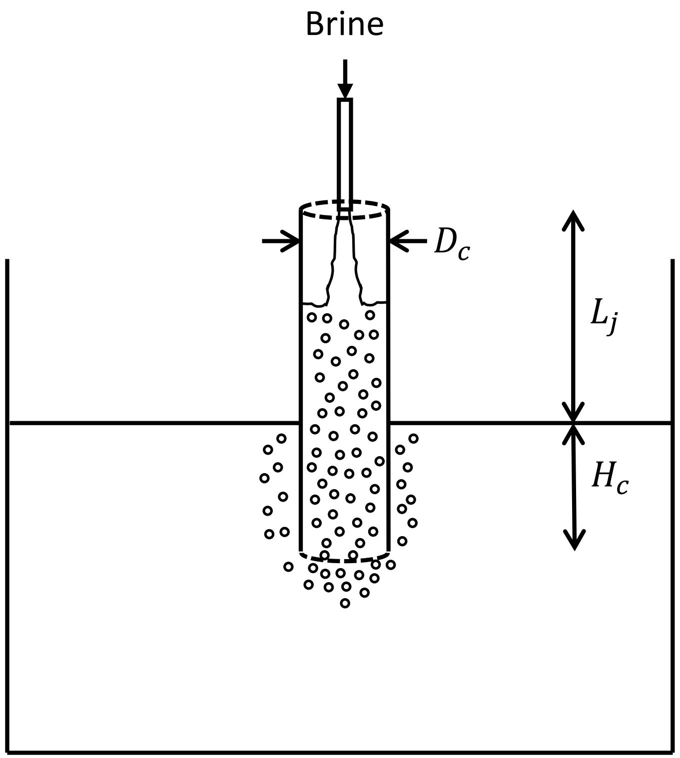




- Again, non-monotonic behavior wrt L_j
- Superior performance of confined jets for range of L_j (for H_c = 10 cm)

Confined jets: effect of downcomer diameter





- For small D_c, flow exiting downcomer is uniform across downcomer cross-section. The momentum of flow exiting is smaller for large D_c which is why dilution first decreases with D_c.
- For large D_c, flow is not uniform. With increasing D_c, more ambient water is available for entrainment. Thus, dilution increases with D_c.

Optimization of downcomer design

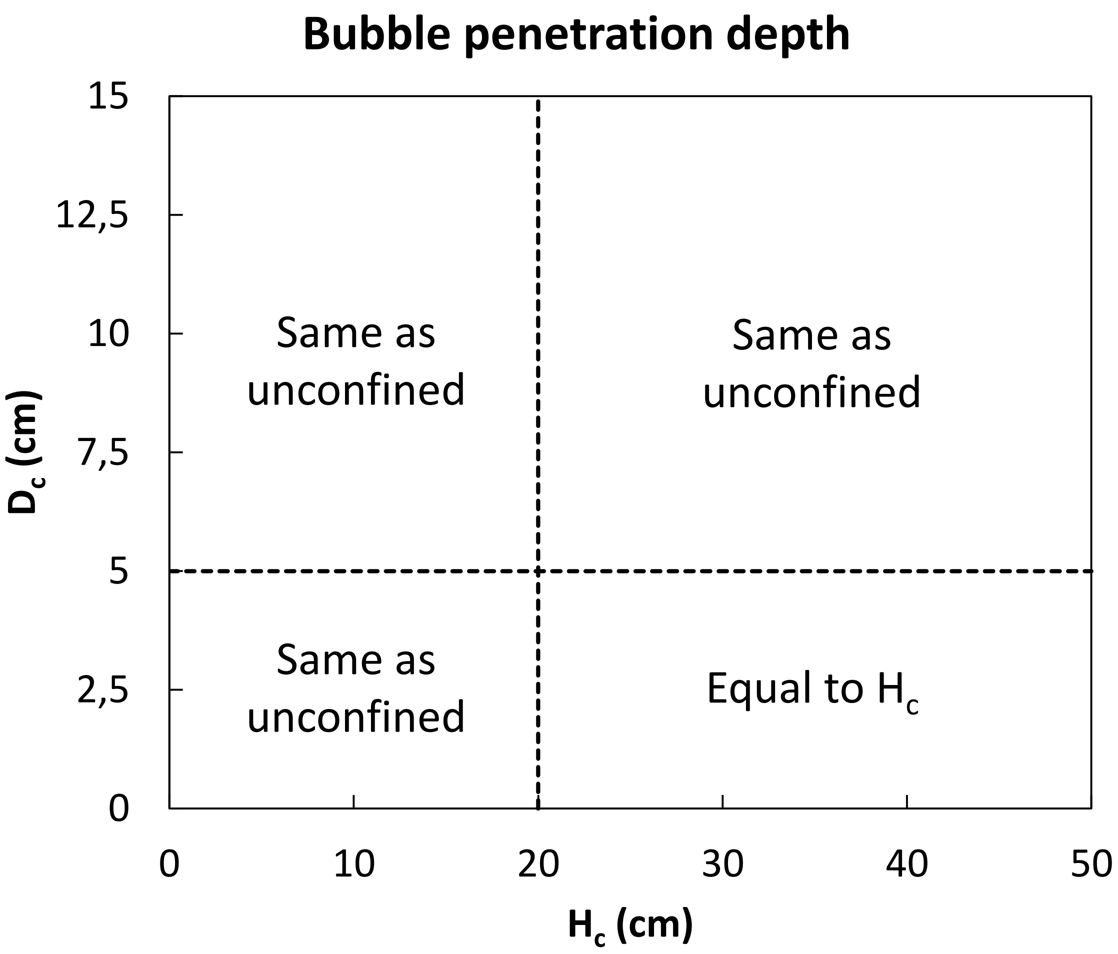
Find optimal design (D_c and H_c) to maximize two objectives:

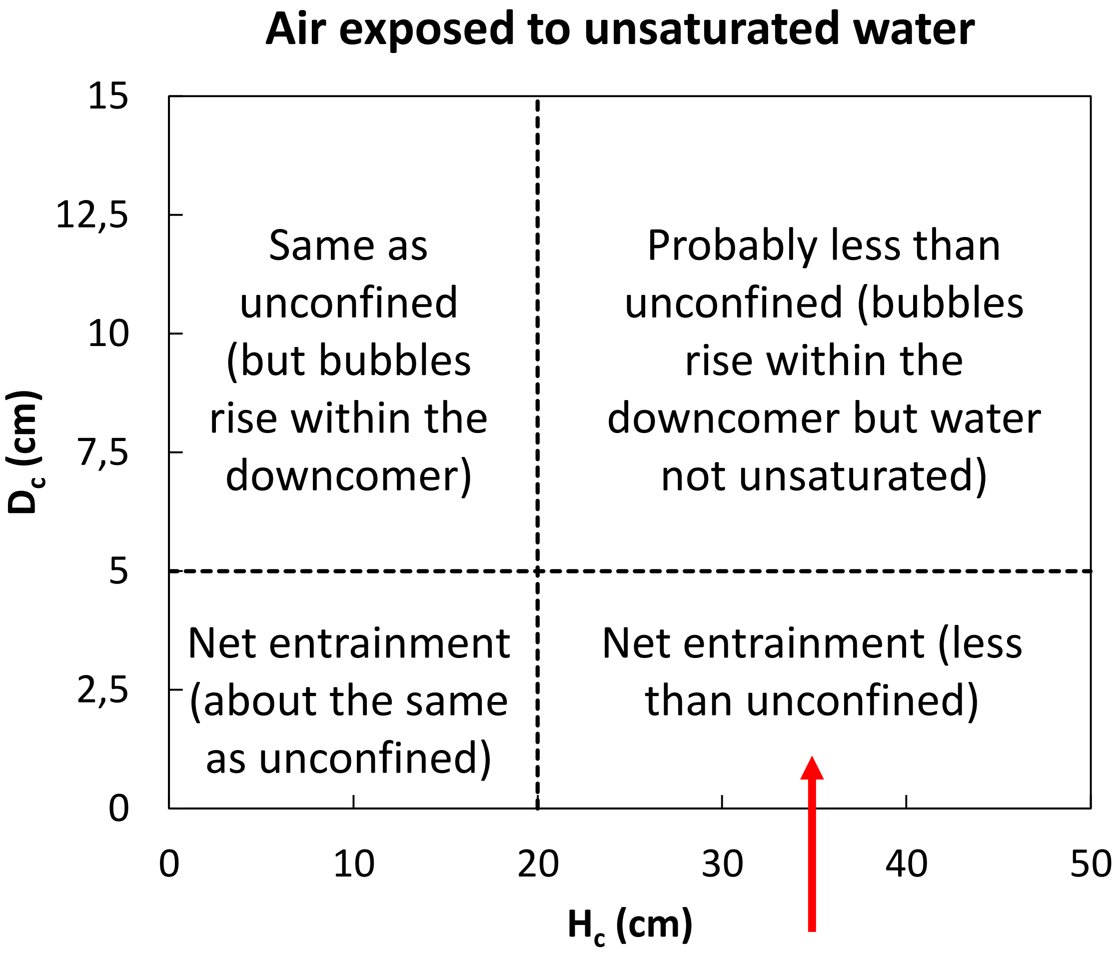
- Aeration
- Dilution

Aeration depends on:

- Bubble penetration depth (increases contact time for dissolution)
- Amount of air exposed to unsaturated water

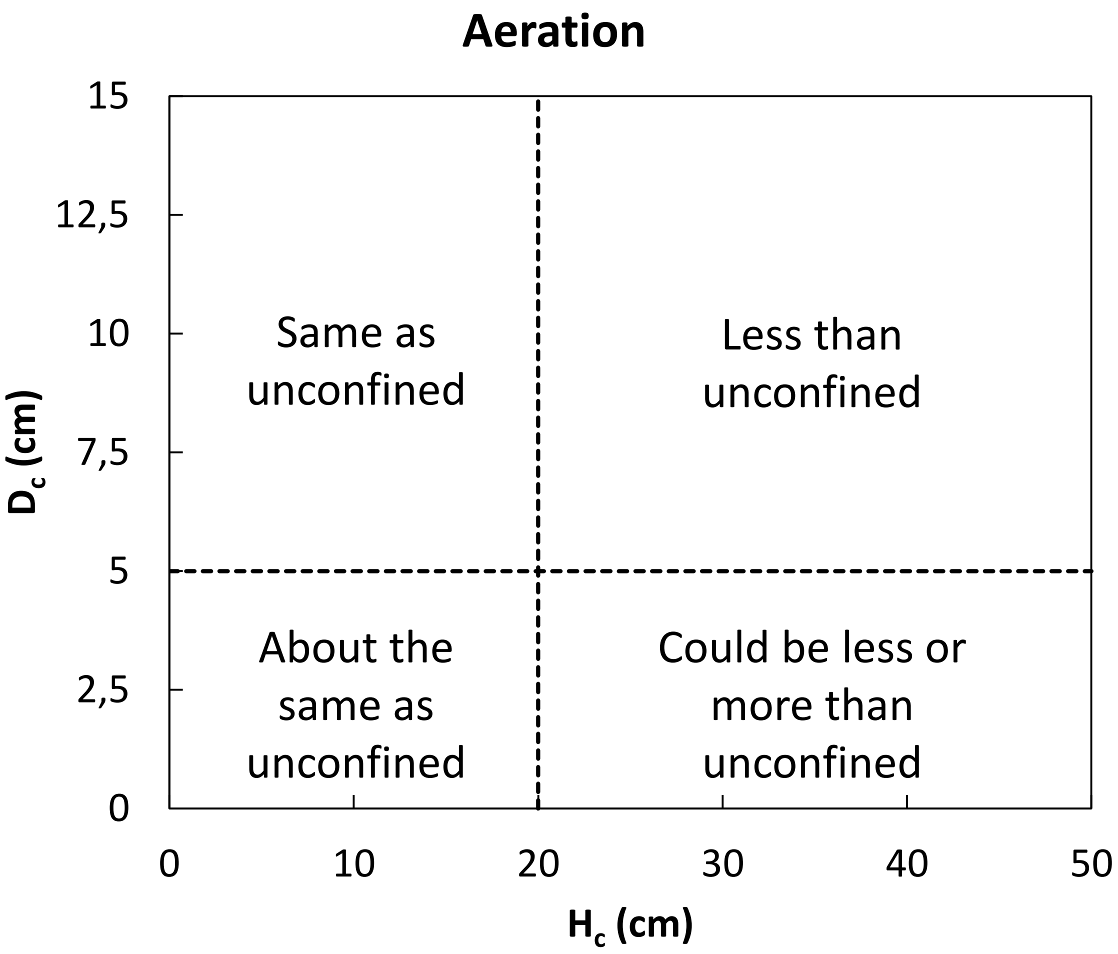
Aeration

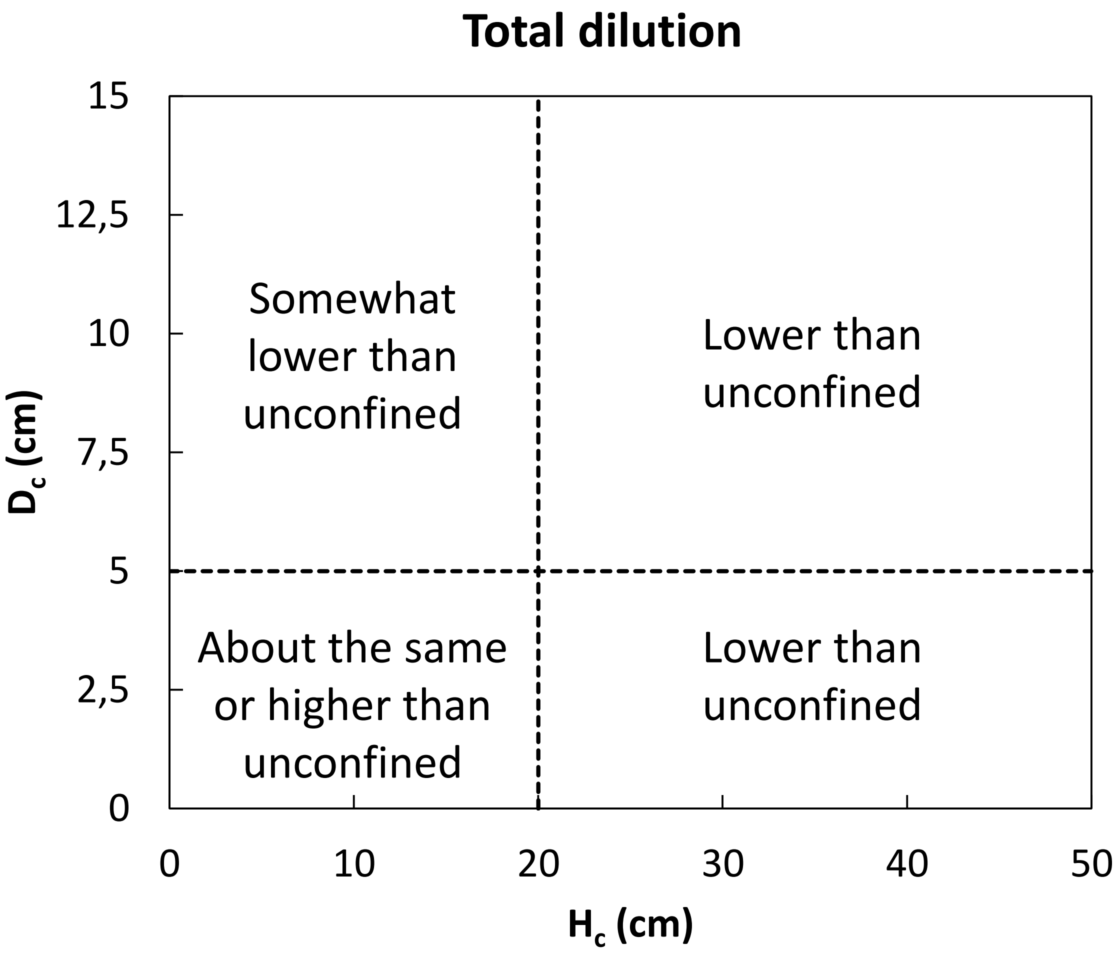




Dis-entrained air does not contribute to aeration because the water within the downcomer is close to saturation

Aeration and dilution





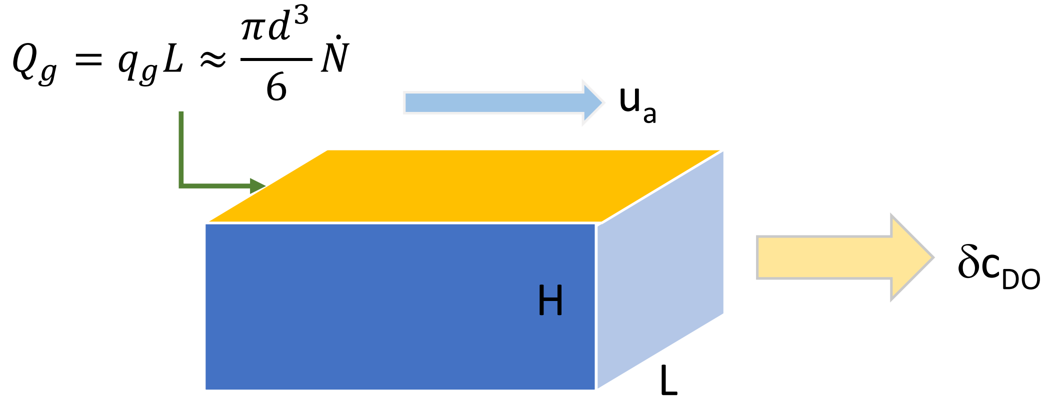
Plunging liquid jet – mass transfer

Added oxygen to water column

- $\delta c_{DO} = \frac{\text{Oxygen flux}}{\text{Water flux}} = \frac{J}{u_a HL}$
- $J = Ak(c_s - c)$ where $A = N\pi d^2$
- N = number of bubbles in contact w/water

  $= \text{Bubble rate in} \times \text{contact time} = \dot{N}t$

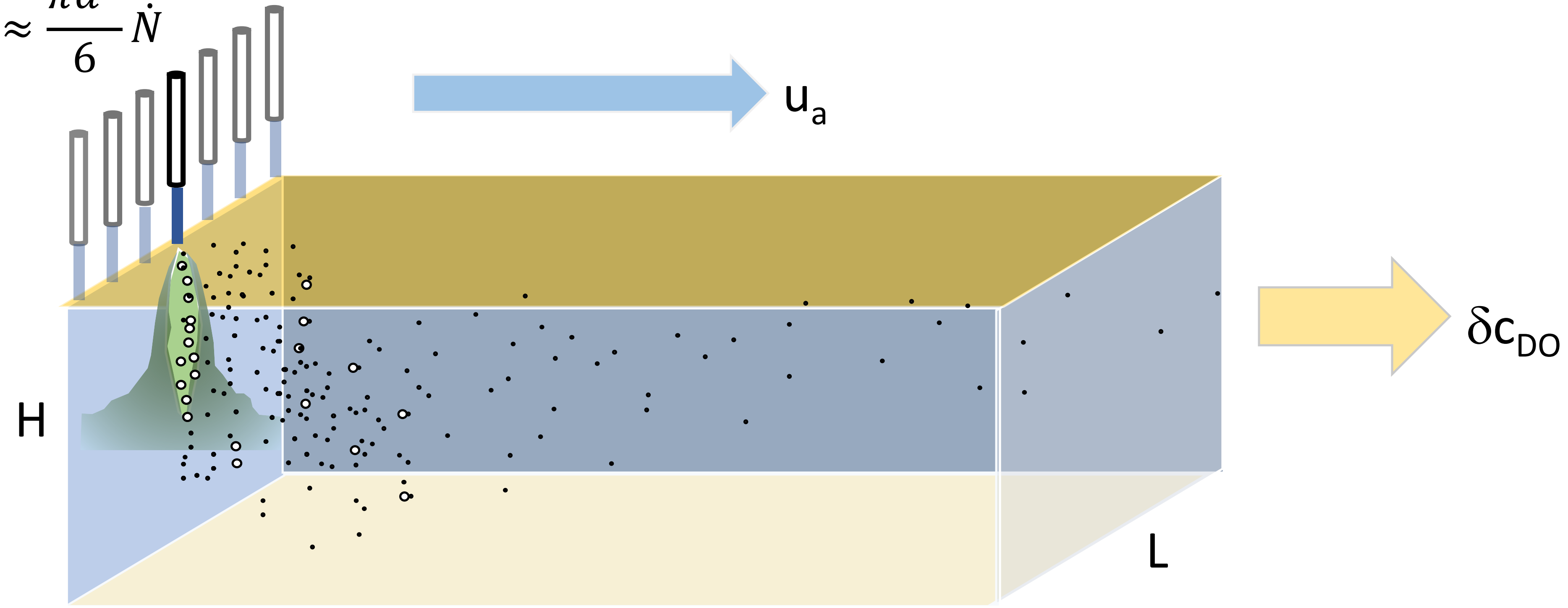
- Gas flow rate in = $Q_g = q_g L \approx \frac{\pi d^3}{6}\dot{N}$
- Contact time: estimate with $t = \frac{H_p}{u_b}$
- H_p = depth of penetration (this study)
- u_b = elliptical bubble rise velocity, k = mass transfer coefficient (Clift, et al., 1978)
- q_g = air entrainment rate (Bin, 1993)



$$\delta c_{DO} = \frac{N\pi d^2 k(c_s - c)}{u_a HL} = \frac{6 q_g H_p k(c_s - c)}{d u_b u_a H}$$

Plunging liquid jet – mass transfer

$$Q_g = q_g L \approx \frac{\pi d^3}{6}\dot{N}$$



$$\delta c_{DO} = \frac{N\pi d^2 k(c_s - c)}{u_a H L} = \frac{6 q_g H_p k(c_s - c)}{d u_b u_a H}$$

Aeration potential

Case	Initial DO concentration (mg/L)	n	u_a (m/s)	d (cm)	L_j (m)	u_b (m/s)	d_0 (m)	H_p (m)	k (m/s)	Change in DO concentration (mg/L)
Base	2	6	0.007	0.5	3	0.2	0.2	2.2	4.2 e-4	**2.7**
Higher background DO	5	6	0.007	0.5	3	0.2	0.2	2.2	4.2 e-4	**1.0**
More jets, same total flowrate	2	10	0.007	0.5	3	0.2	0.2	1.8	4.2 e-4	**2.2**
Larger ambient current	2	6	0.2	0.5	3	0.2	0.2	2.2	4.2 e-4	**0.1**
Smaller bubbles	2	6	0.007	0.25	3	0.2	0.2	2.2	8.4 e-4	**10.9***
Shorter jet length	2	6	0.007	0.5	1	0.2	0.2	2.0	4.2 e-4	**1.1**
Larger nozzle diameter	2	6	0.007	0.5	3	0.2	0.5	2.0	4.2 e-4	**1.4**
Larger ambient current, smaller bubbles	2	6	0.2	0.25	3	0.2	0.2	2.2	8.4 e-4	**0.4**

Significant increase in dissolved oxygen, especially with smaller bubbles

Is a plume on the water surface acceptable?

Outfalls often designed to hide plume beneath the surface. With PLJR or CPLJR the plume is obviously on the surface.

But many outfalls are surface discharges already.

Educational opportunity (show people how their water is made).

An art installation?

Major conclusions

- PLJRs can provide both effective aeration and dilution.
  - But, calculated aeration, in particular, needs field testing.
- PLJR dilution comparable to that of submerged brine outfalls.
  - Short jet lengths less effective than longer lengths (splashing more harmful than increased momentum).
- CPLJRs generally provide less dilution than (unconfined) PLJRs.
  - Downcomers increase bubble penetration, but reduce bubble access to (unaerated) ambient water.
  - Exception appears to be CPLJRs with short and narrow downcomers which gives better dilution than (unconfined) PLJRs. These need more study.
- PLJRs seem particularly suited for shallow water.
  - Shallow depths provide suitable anchorage, e.g., mounting outfall pipe beneath rigid piers.
  - But sluggish circulation in shallow water may result in poor flushing, reducing total dilution.

Thank you