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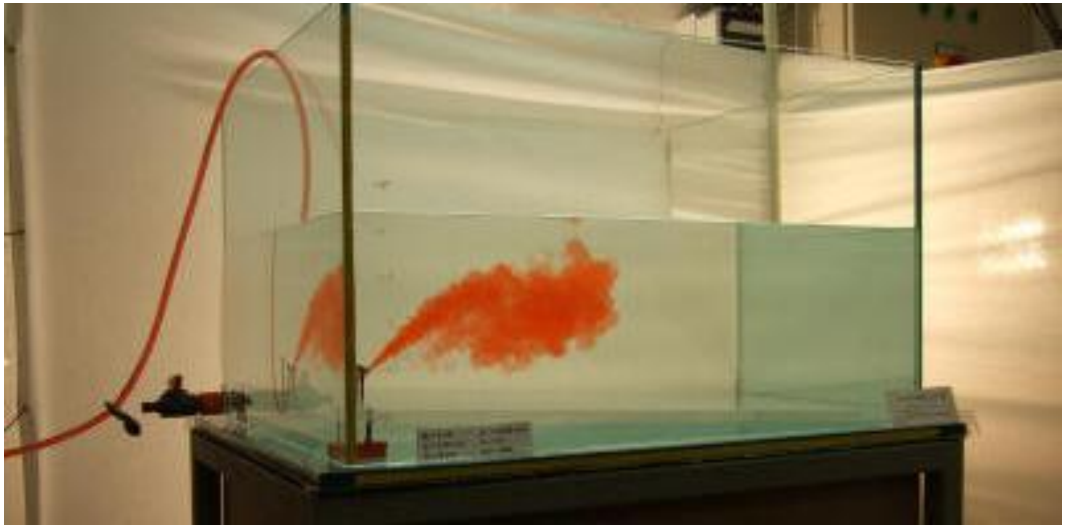
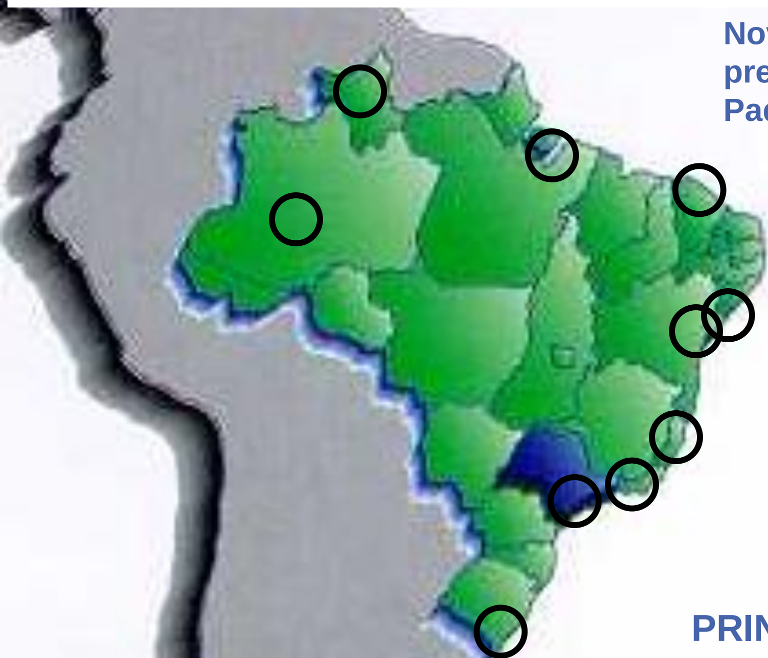
Marine Outfall Systems



EMISSÁRIOS SUBMARINOS NO BRASIL



Novos emissários recém construídos e previstos no RJ (Barra da Tijuca, Icaraí, Paquetá), no ES (Vitória, Guarapari), etc

Píer do emissário da Barra da Tijuca – 5 km de extensão para uma vazão final de 5,3 m³/s

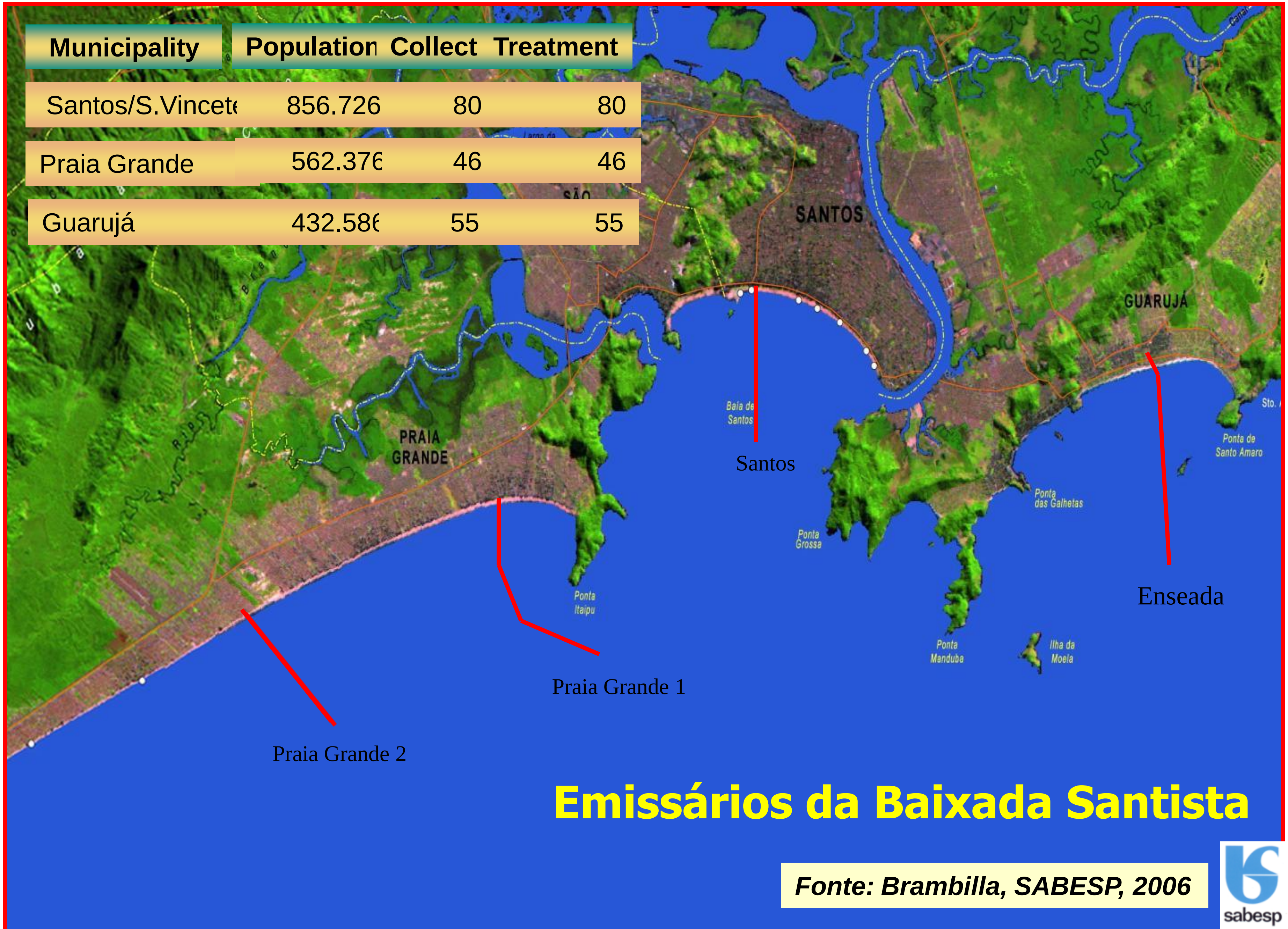
Novo SDO Icaraí em Niterói – emissário de 3.300 m dentro da Baía de Guanabara para uma vazão de 0,95 m³/s de esgoto

PRINCIPAIS EMISSÁRIOS DE ESGOTO DOMÉSTICO

Item	Local	Diâmetro (m)	Extensão total (m)	Profundidade descarga (m)	Vazão de projeto (m^3/s)	Material	Início da operação
1	Belém - PA	0,80	320	5	0,60	Concreto	*
2	Fortaleza – CE	1,50	3.200	12	4,80	Aço, revestido c/ concreto	1979
3	Salvador – BA	1,75	2.350	28	6,80	Concreto Armado	1975
4	Aracruz – ES	1,00	1.100	*	2,00	Polipropileno	*
5	Ipanema – RJ	2,40	4.325	26	12,00	Concreto Protendido	1975
6	Poá - Porto Alegre – RS	1,26	733	12	2,70	Aço	*
7	Manaus – AM	1,00	3.600	*	2,20	PEAD	*
8	Boa Vista – RR	0,35	1.250	*	*	PEAD	*
9	Maceió – Casal - AL	1,34	3.100	15	4,20	Aço, revestido c/ concreto	*
10	Santos – José Menino – SP	1,75	4.000	10	7,26	Aço, revestido c/ concreto	1979
11	Guarujá – Enseada – SP	0,90	4.500	14	1,447	PEAD	1998
12	Praia Grande – Praia do Forte – SP	1,00	3.300	12,5	1,041	PEAD	1993
13	Praia Grande – Vila Tupi – SP	1,00	3.415	13	1,361	PEAD	1993
14	São Sebastião – Praia das Cigarras – SP	0,16	1.068	8,5	0,0116	PEAD	*
15	São Sebastião – Araçá – SP	0,40	1.061	8	0,140	PEAD	*
16	Ilhabela – Saco da Capela – SP	0,25	220	24	0,030	PEAD	*
17	Ubatuba – Enseada – SP	0,20	300	*	*	PEAD	Previsão [illegible]

Fonte: Brambilla, SABESP e Trevisan et al.

Municipality	Population	Collect	Treatment
Santos/S.Vincete	856.726	80	80
Praia Grande	562.376	46	46
Guarujá	432.586	55	55



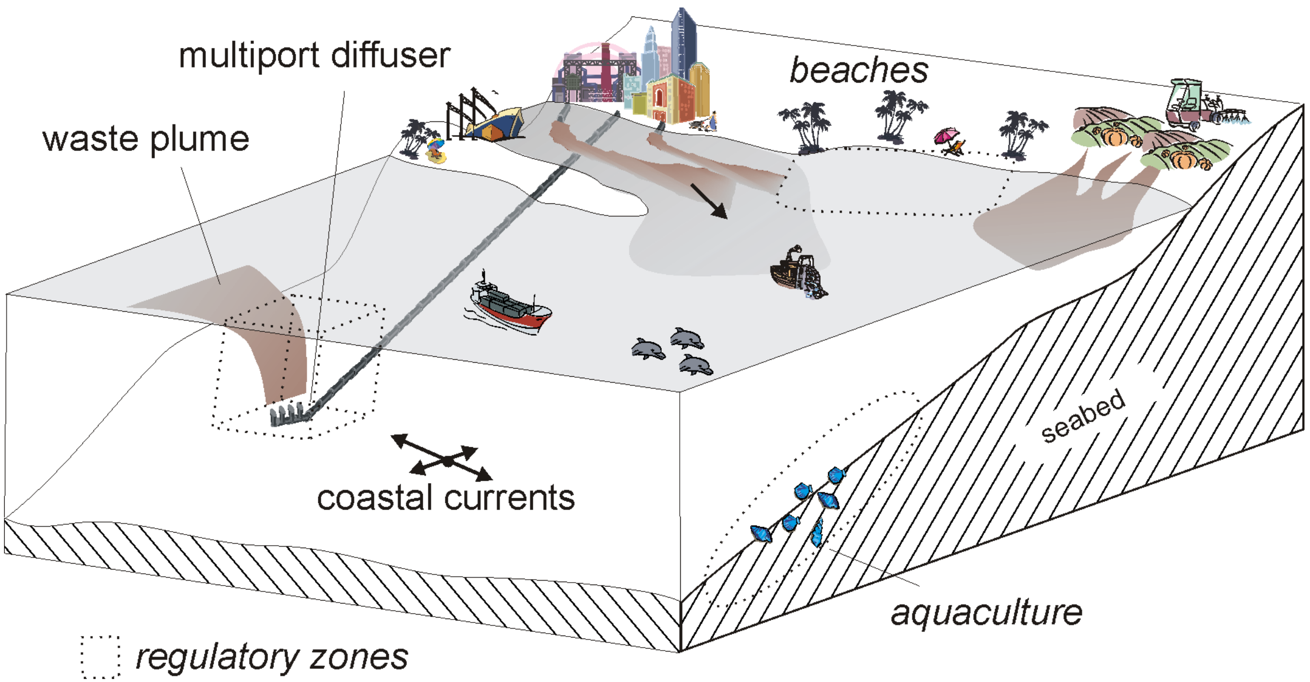
Emissários da Baixada Santista

Fonte: Brambilla, SABESP, 2006

sabesp

Impactos ambientais

- Impactos locais (devido a um lançamento individual)
  -> "altas" concentrações de substancias
  dependendo do tratamento e local de descarga
- Impactos regionais
  -> "altas" cargas de substancias
  efeitos de acumulação dependendo do corpo receptor
- Grandes diferenças de escalas e processos associados



Legislação de descargas

- Directivas internacionais
- Directivas nacionais

Poluente	Concentração limite do efluente CLE	Concentração limite no ambiente CLA	CLE/CLA
DBO 5	Geralmente definido so para rios (esgoto bruto: 300mgl/l)	3 mg/l (Cartagena)	100
Temperatura	10°C acima ambiente (Worldbank)	3°C acima ambiente (Worldbank)	3
Cadmio	0.5 mg/l (83/513 EEC)	1µg/l (76/464 EEC)	500
Tricloretano	0.1 mg/l (AbwV, DE)	10 µg/l (76/464/EEC)	10

↑ Efeitos letais

↑ Efeitos cronicos

↑ **diluição necessaria 2 a 500**

Toxicidade de cobre

Source: Lattemann & Höpner 2003

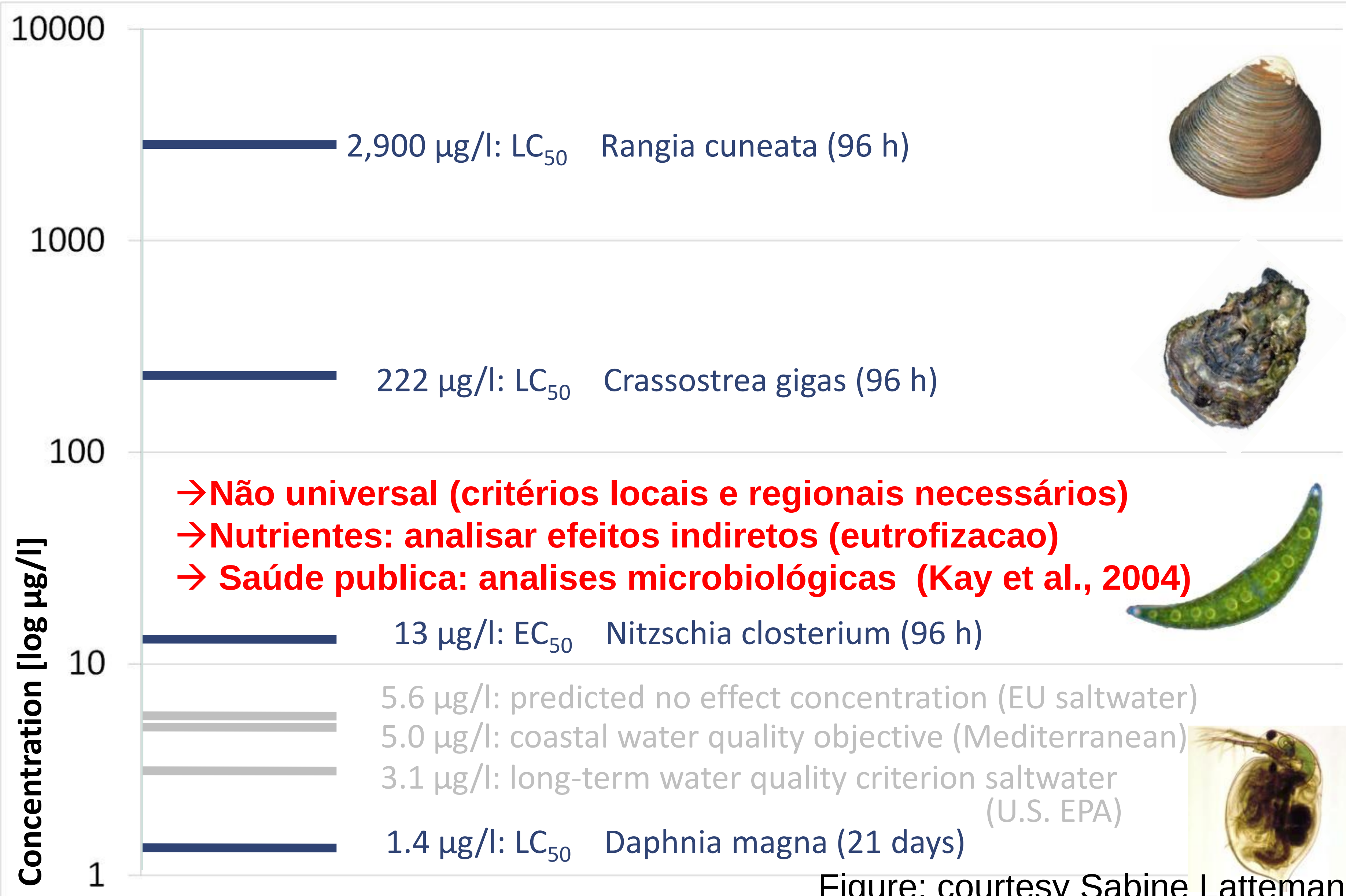


Figure: courtesy Sabine Lattemann

Diluição e tratamento

Diluição =

$$\frac{\text{concentração efluente}}{\text{concentração (limite) no ambiente}}$$

	Diluição necessária para esgoto bruto	*Diluição necessária após o tratamento primário*	*Diluição após o tratamento secundário*	*Diluição necessária após o tratamento terciário*
DBO [mg.L^{-1}]	10	8	2	1
Nitrogênio tot. [mg.L^{-1}]	5	4	4	0
Fósforo tot. [mg.L^{-1}]	4	3	3	0
Sólidos susp. Tot. [mg.L^{-1}]	22	9	3	1
Coliformes tot. [MPN.(100 mL)$^{-1}$]	10^4 a 10^8	10^3 a 10^7	10^3 - 10^7	500 - 10^6

Fonte: Mayra Ishikawa, 2016

Consequencias e medidas de mitigação

e.g. esgoto: nutrientes (DBO, P), coliformes,...

Coliformes fecais:

- Esgoto bruto $10^6 - 10^8$ e.coli/100ml Media: 10^7

Tecnologias de tratamento → CLE

		Fator de redução de coliformes
tratamento primario (mecanico)	Reduz nutrientes (lodo!)	1.5 – 3
primario avancado (floculacao quimica)		10 – 100
secundario (biologico)		100 – 1000
terciaro (quimico)		1000 – 10.000

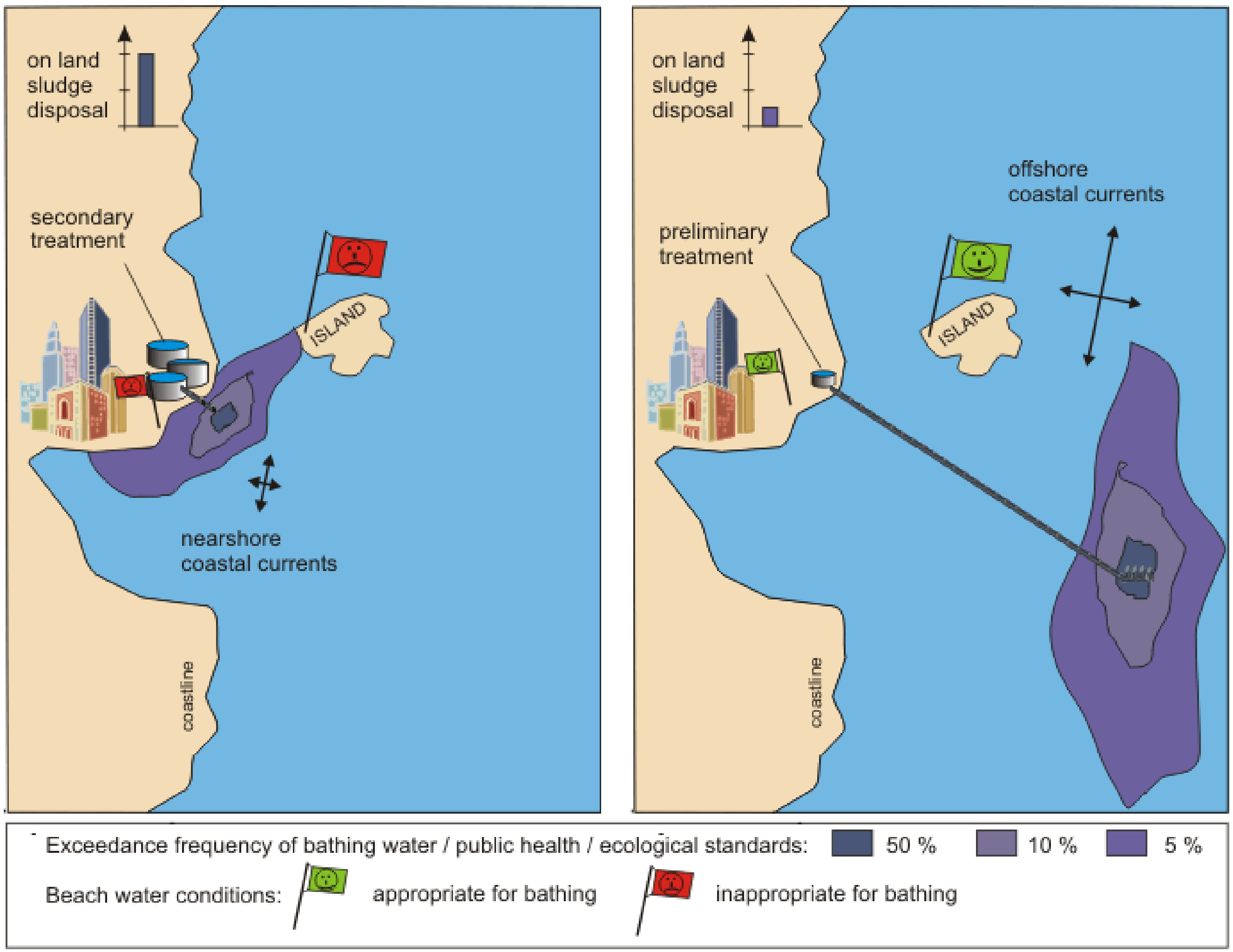
Tecnologias de mistura

	Fator de diluição
Descarga superficial na costa	2 - 10
Descarga submersa de um orificio	5 - 50
Descarga submersa de varios orificios (difusor)	10 - 500

- EC Conc. limite balneabilidade 500e.coli/100ml Diluição : 20.000

Sistema de emissário

- Combinação e complementação de tratamento **e** emissário
- Critérios de desenho: favorecer critérios de qualidade da água (balneabilidade, potabilidade, classes), e do sedimento e critérios biológicos em vez de critérios baseado exclusivamente em tecnologias



Nivel de tratamento necessario

Definição do nível de tratamento necessário

Diluição inicial

$$C_e = C_{lim} + D\,(C_{lim} - C_b)$$

Concentração efluente

Concentração limite no ambiente após zona de mistura legal

Concentração “background”

Mitigation measures

- contaminant reduction at source:
- substitution of contaminants
  - e.g. using "green" chemicals with less toxicity and higher biodegradability
- install treatment technologies
  - e.g. using higher level treatment
- improve discharge technology
  - balanced with water body usage and natural assimilation processes (e.g. multiport diffuser)

Impact evaluation – methods

= predictions about expected effects, based on:

Field experiments

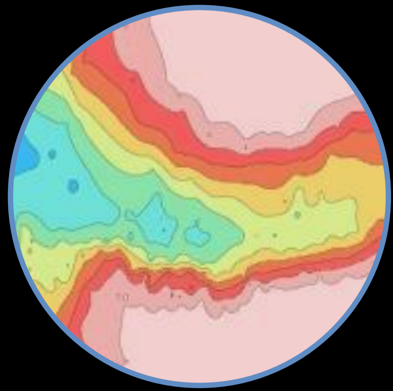
- rhodamine dye tests (Perth SWRO)

Laboratory experiments

- effluent toxicity tests (Carlsbad)

Analogies & judgement

- similar desalination projects



Computer models

- hydrodynamic modelling

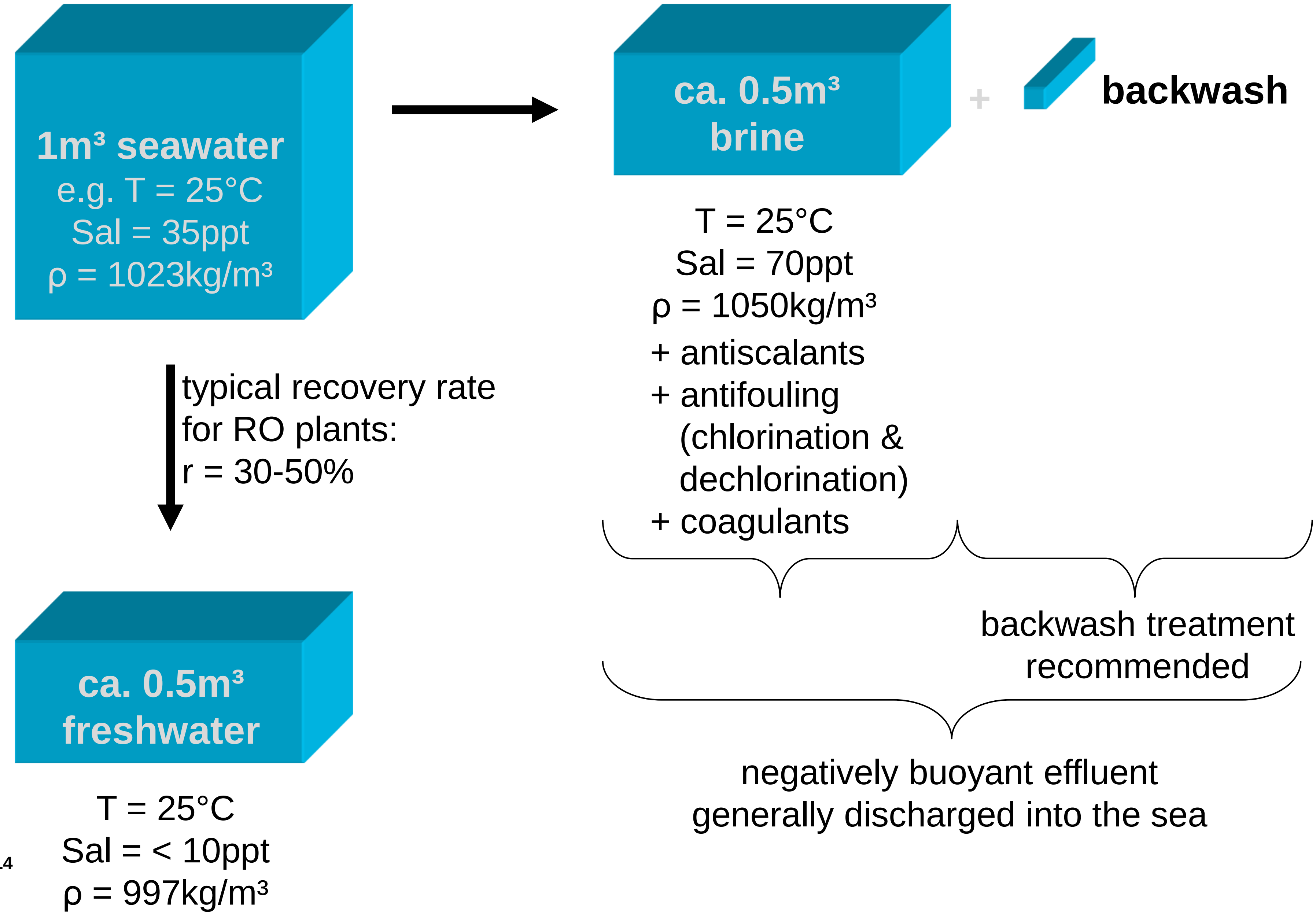
Picture: Western Australian, (Crisp et. Al 2007)

Picture: Voutchkov & Dietrich 2007

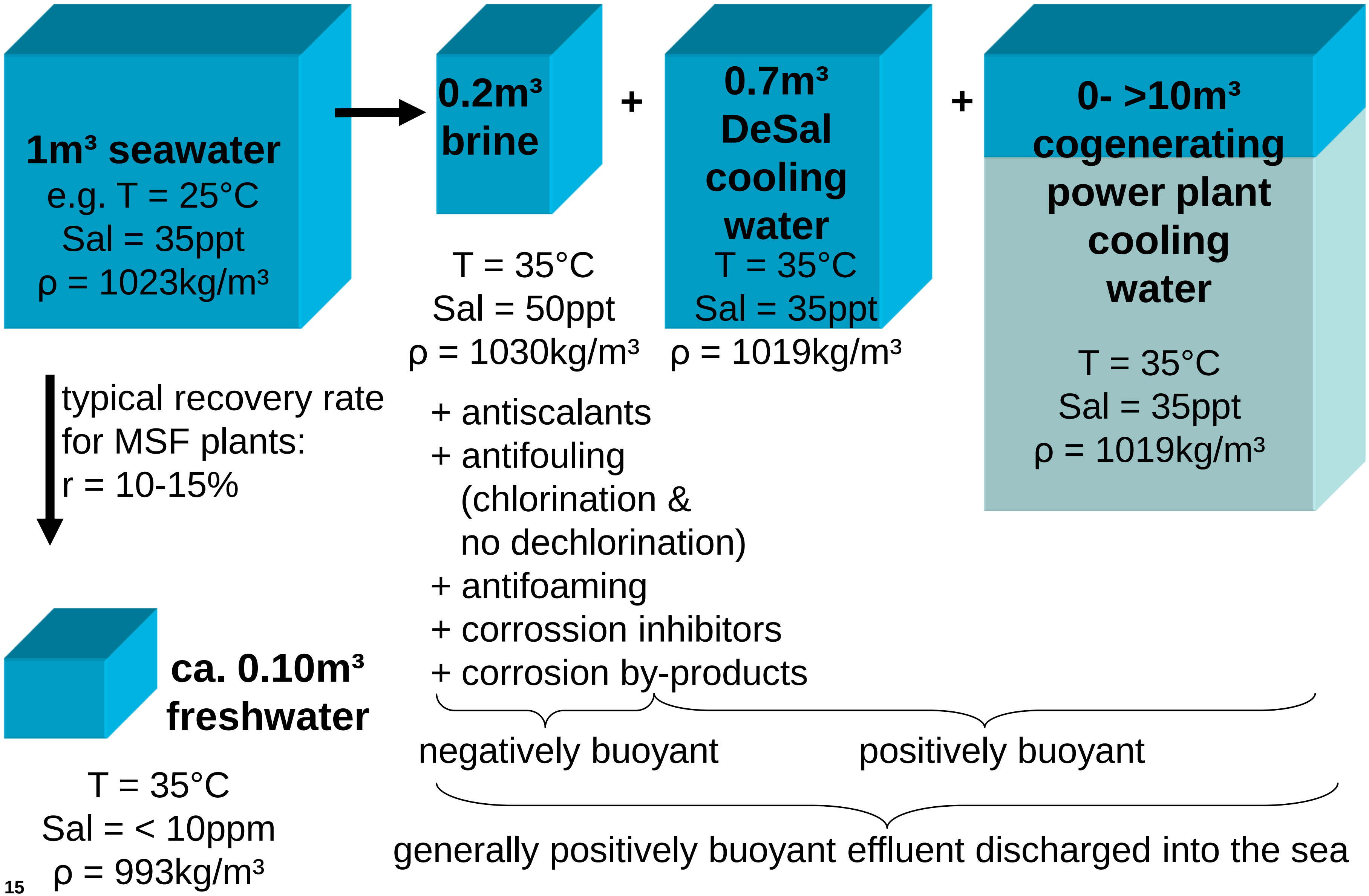
Example

- Desalination Plant Outfall System
- = multi component waste discharge
- = typical example of industrial discharge

Effluent characteristics for Reverse Osmosis (RO)



Effluent characteristics for thermal desalination (e.g. MSF)



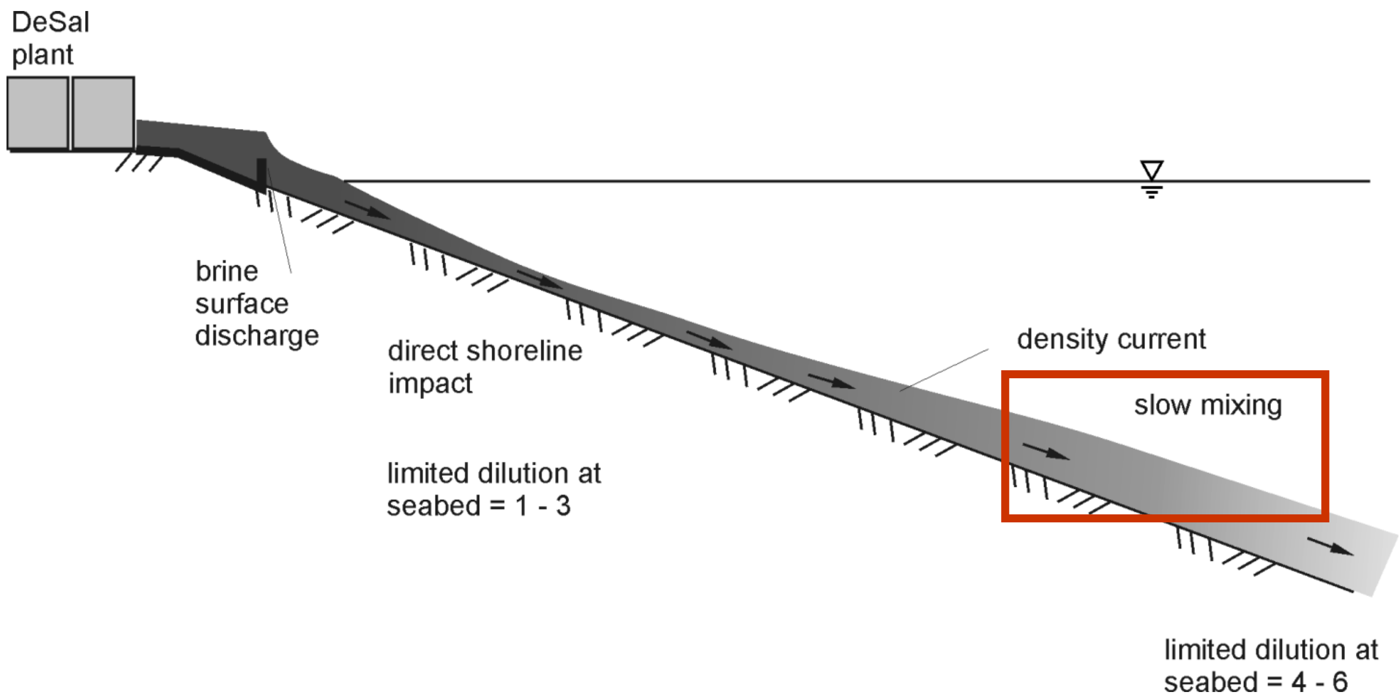
Outfalls

- Shoreline surface discharge
- Offshore submerged single port discharge
- Offshore submerged multiport diffusor discharge

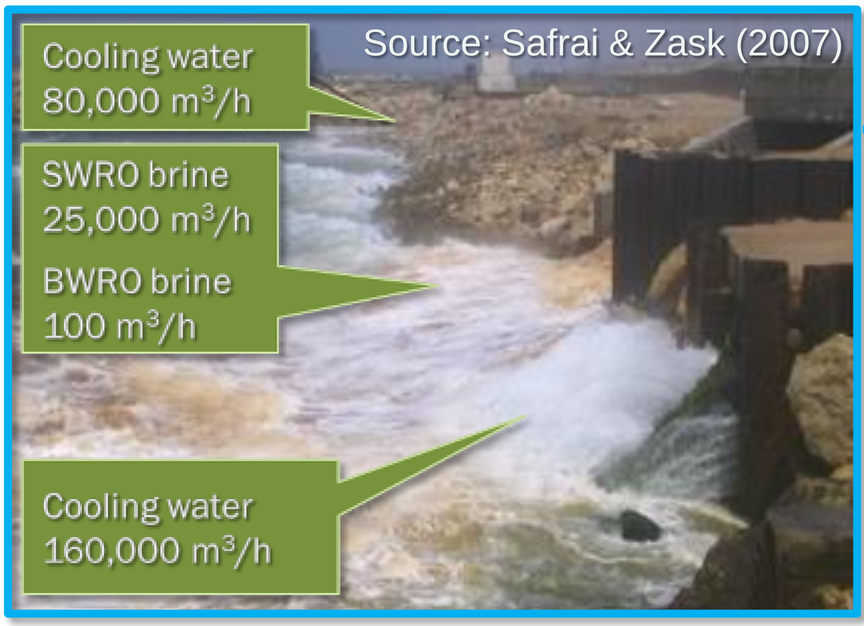
Shoreline surface discharge TRADITIONAL!

- Example 1: RO-plant discharge, negative buoyancy

- density current of high stability develops, flowing down the seabed
- density effects strongly influence mixing characteristics



RO plant in Ashkelon (Israel)



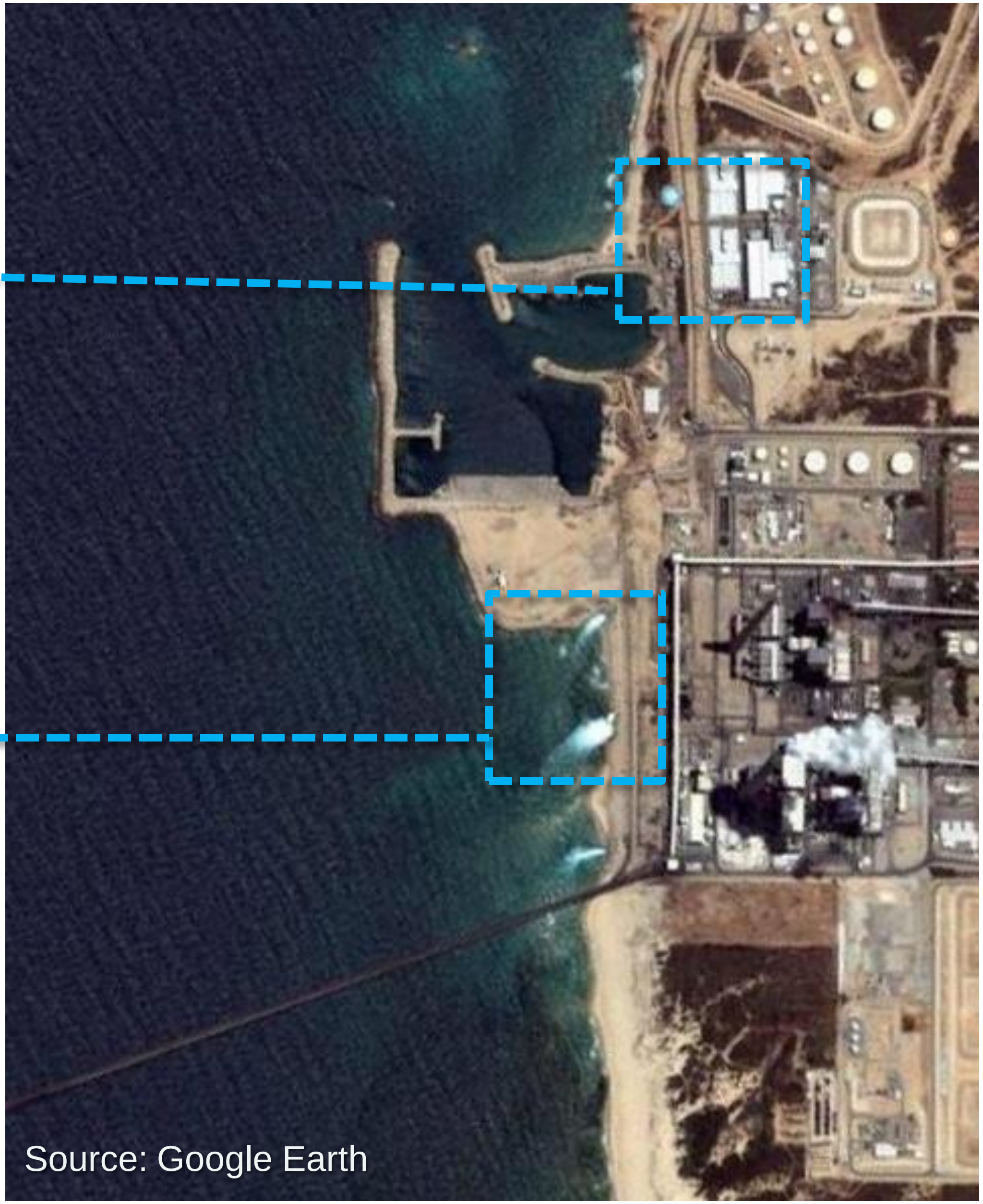
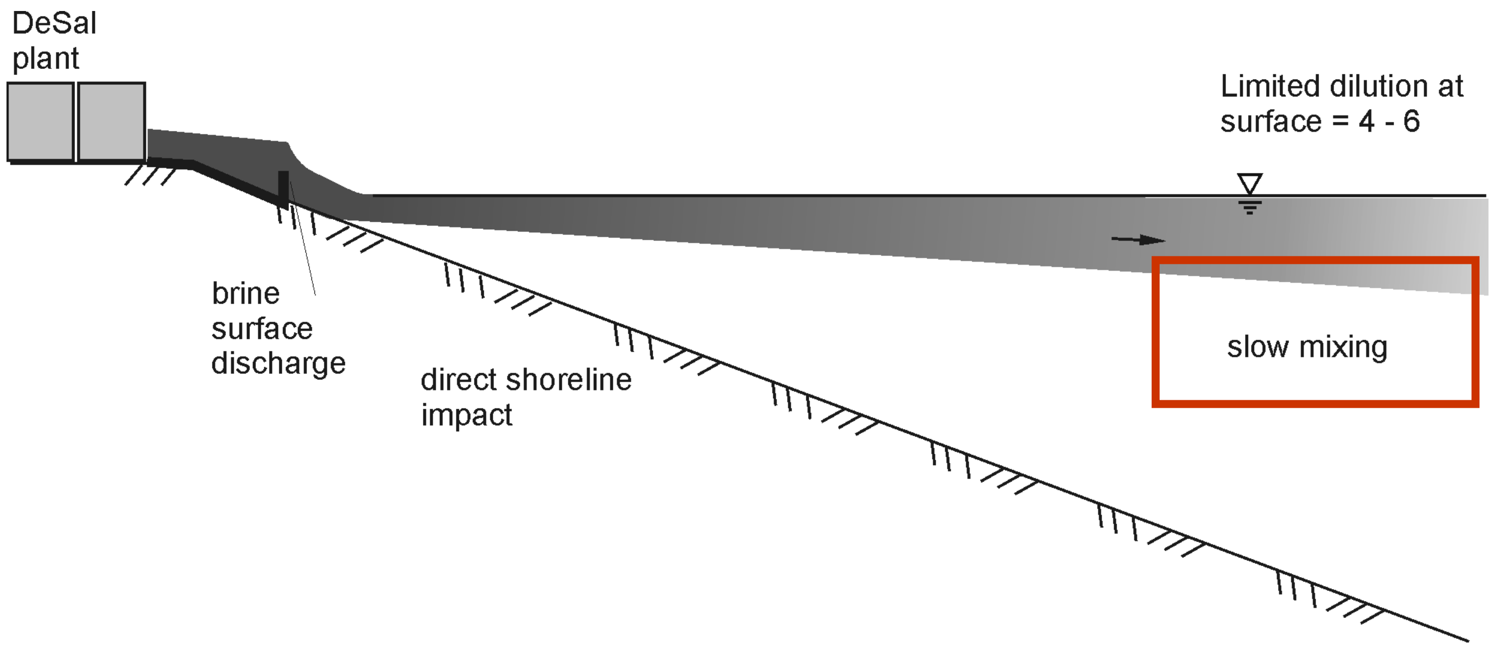



Photo: Rani Amir, Israel Ministry of the Environment
presented by Iris Safrai at the EDS Conference 2007

Shoreline surface discharge TRADITIONAL!

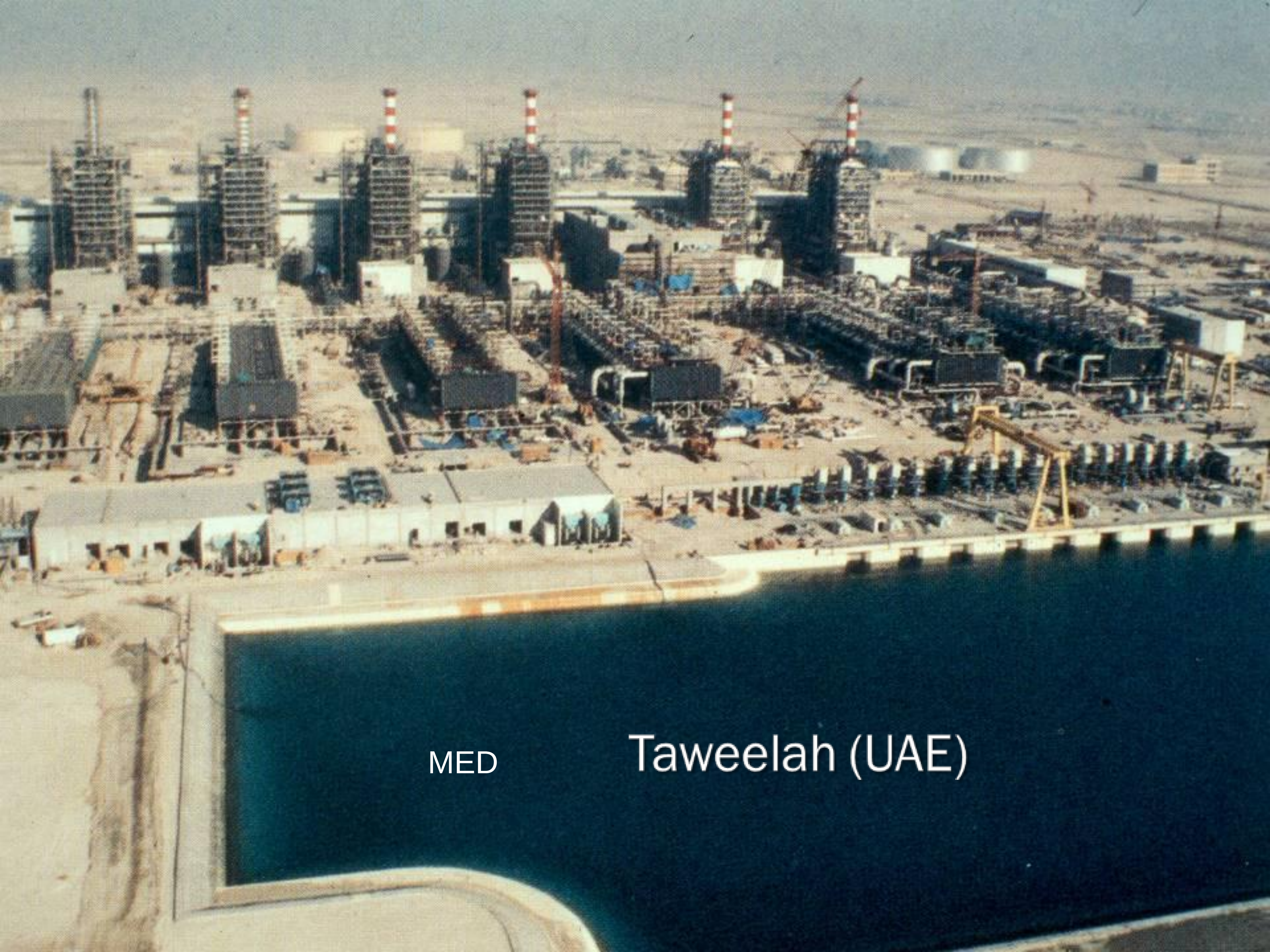
- Example 2: Combined MSF-plant+ cooling water discharge, positive buoyancy
- usually mixing is slow in surface plume




Intake
Lagoon
Outfall
Discharge pond
Intake area
Carlsbad
SWRO plant
(visualization)
Power
Plant
Source: City of Carlsbad and Poseidon Resources 2005

Gulf)


Source: Google Earth
intake
outfall
Image © 2007 DigitalGlobe
© 2007 Europa Technologies
Google
Pointer 26°54'15.90" N 49°47'07.64" E elev 1 ft
Streaming 100%
Eye alt 11214 ft

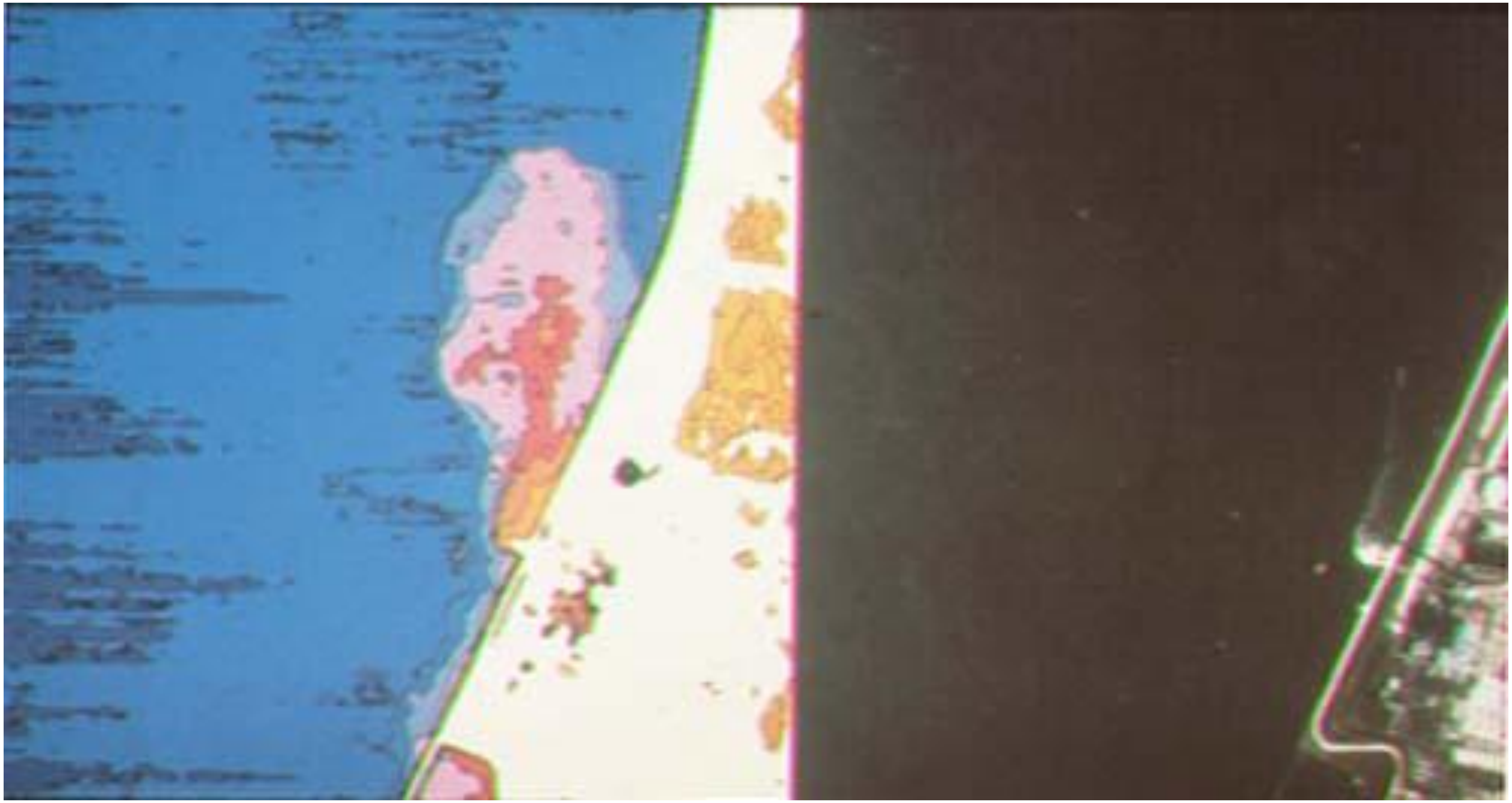

MED
Taweelah (UAE)

MSF Plant Taweelah, Arabian Gulf, 1.12 mio m³/d, Source: Lattemann and Höpner, 2008

Mixing processes

Source: I. Wood, Univ. of Canterbury

Mixing processes



Source: Thermal discharge, Cormix Homepage

Outfall geometry

- Shoreline surface discharge

TRADITIONAL, LOW COST
HIGH VISIBILITY
LOW MIXING
→ **SHOULD BE AVOIDED!**

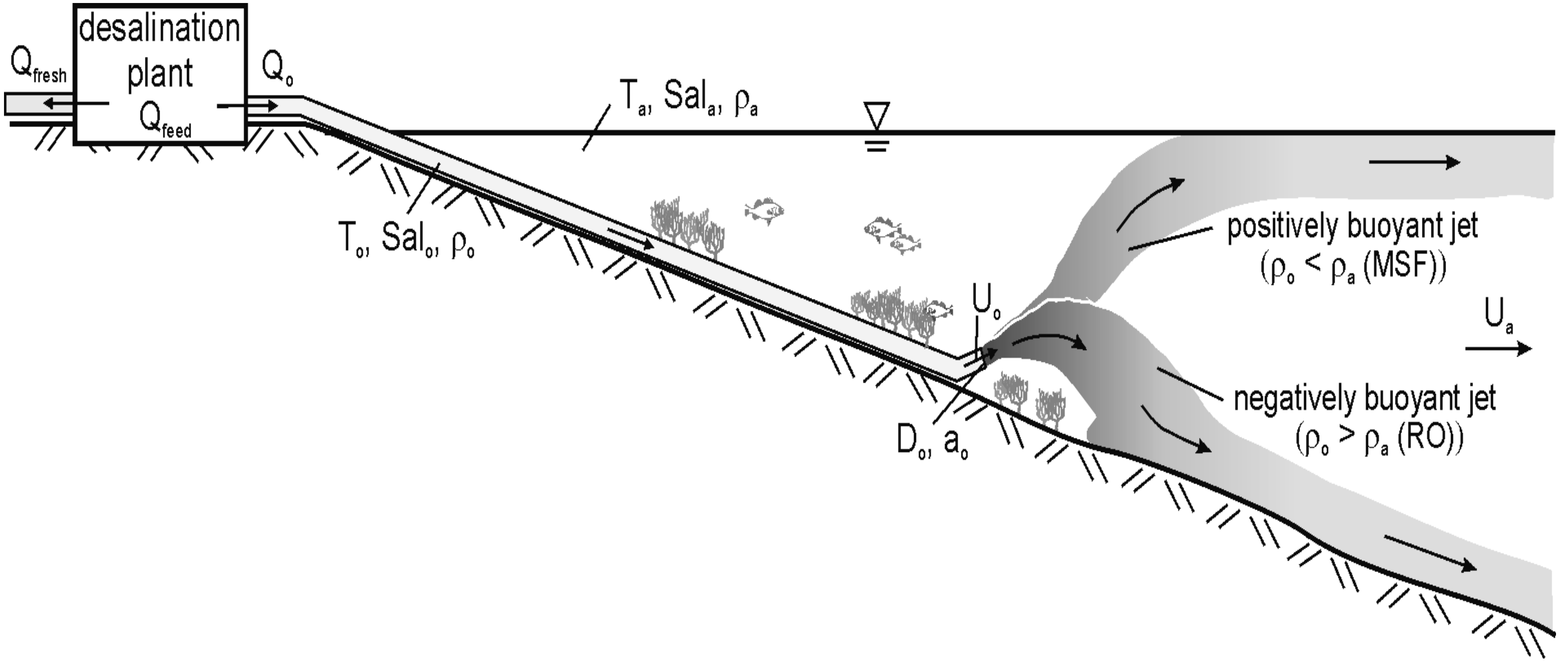
MODERN EFFICIENT MIXING DEVICES
→FLEXIBLE LOCATION (DEPTH)
→HIGH MIXING RATES

- Offshore submerged single port discharge

- Offshore submerged multiport diffusor discharge

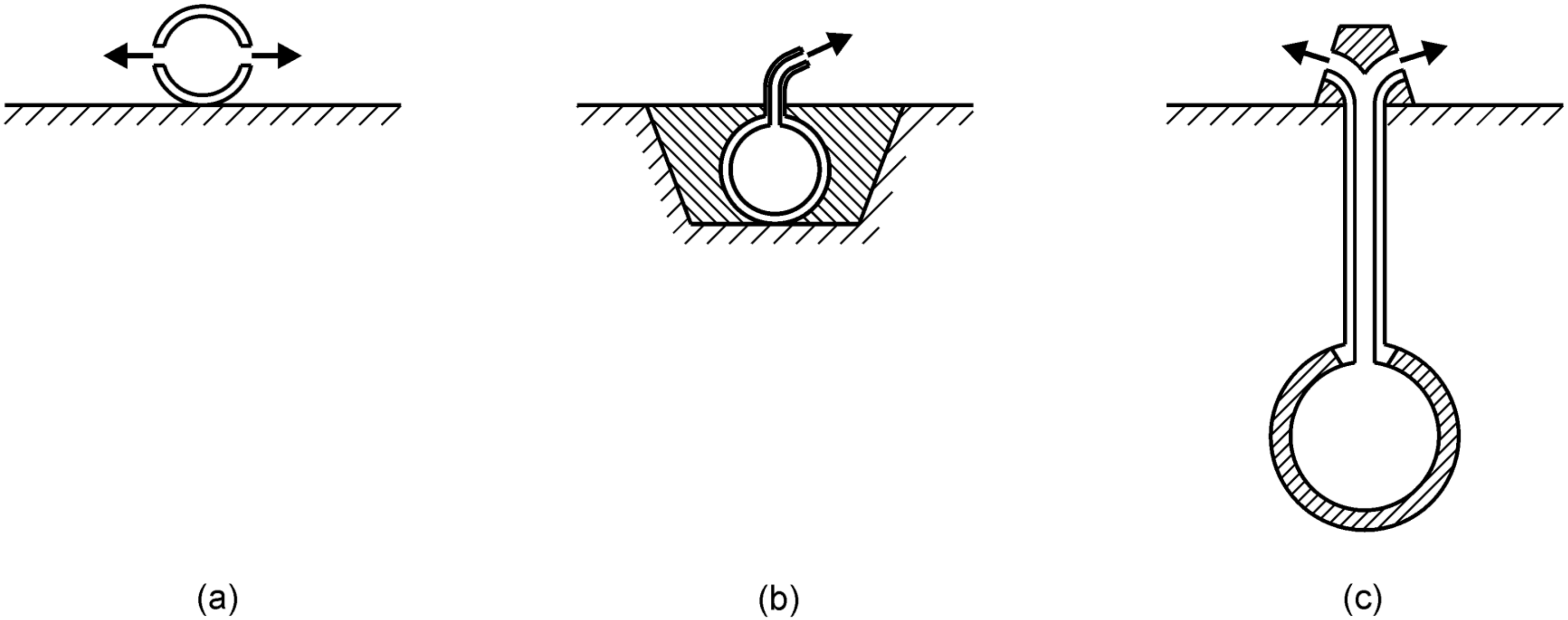
Offshore submerged discharges: efficient mixing devices

- optimized siting of outfalls allows for improved operational conditions and better environmental protection
- optimized mixing device (e.g. **submerged multiport diffuser**) high mixing rates reduce local impacts considerably

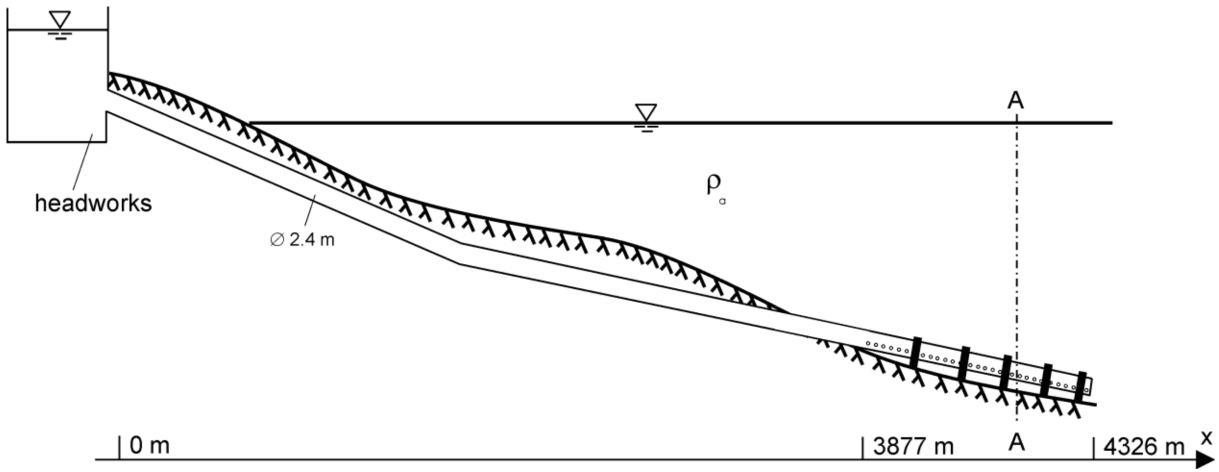


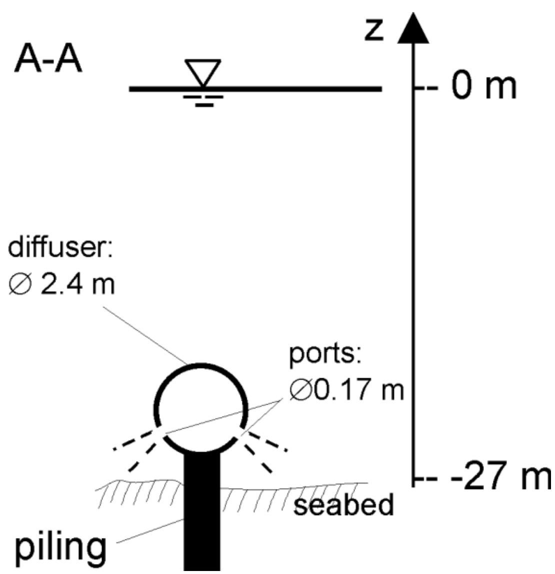
Mixing devices

Construction details



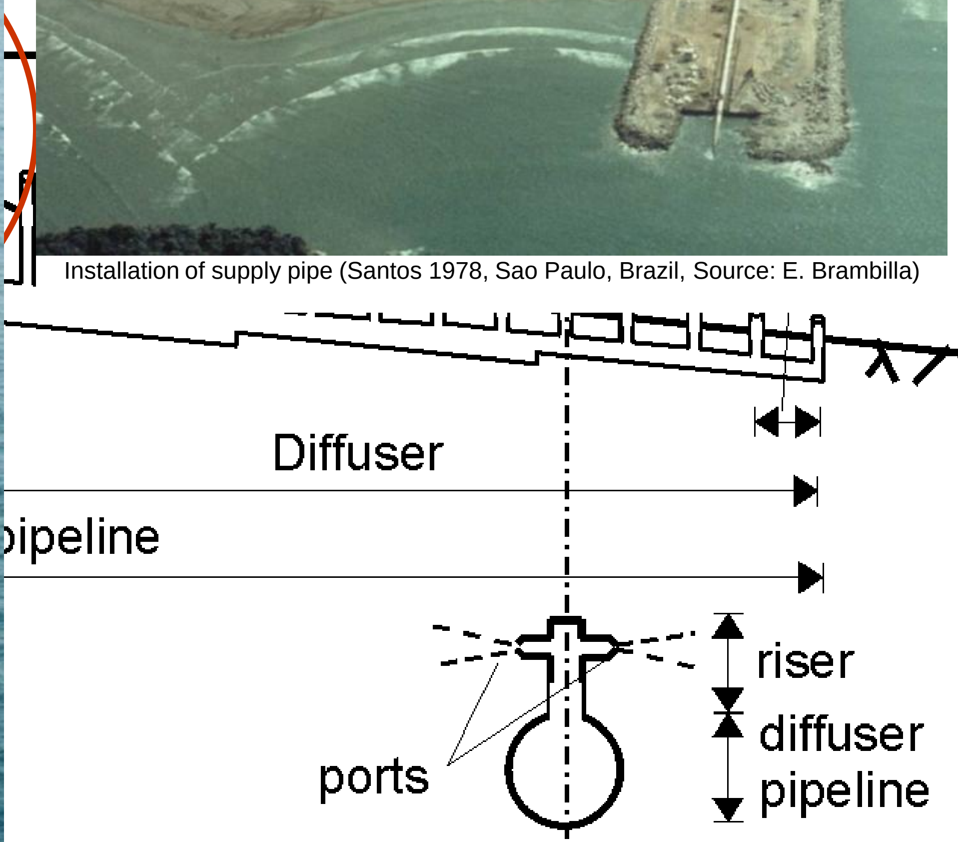
Typical construction details for multiport diffusers in water bodies: (a) Diffuser pipe on bottom with port holes, (b) diffuser pipe buried in trench with short risers, (c) deep tunnel construction with long risers


headworks
∅ 2.4 m
ρa
A
A
0 m
3877 m
4326 m
x


A-A
z
0 m
diffuser:
∅ 2.4 m
ports:
∅0.17 m
-27 m
seabed
piling

Mixing devices

Installation of supply pipe (Santos 1978, Sao Paulo, Brazil, Source: E. Brambilla)

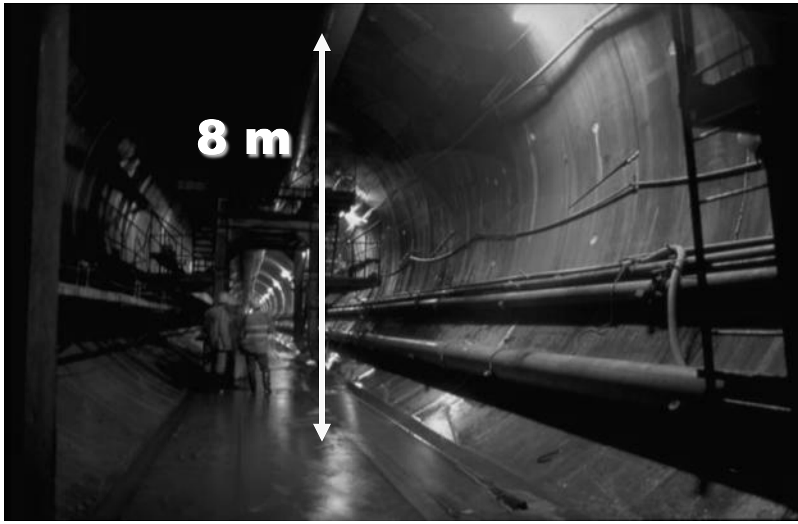


Towing of supply pipe to installation location (Guarujá 1998, Sao Paulo, Brazil, Source: E. Brambilla)

Long outfall pipes

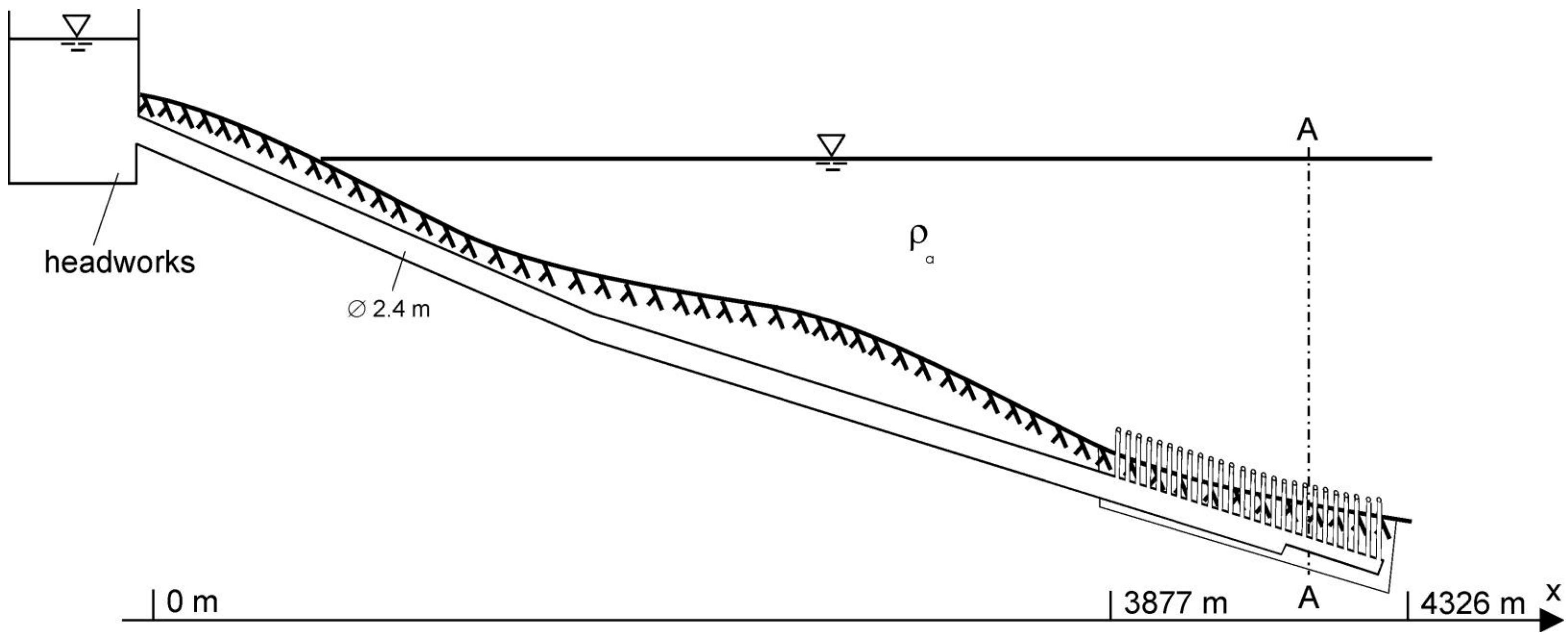
Pipe sections varying from 59 to 164-ft-long and weighing as much as 242 tons.

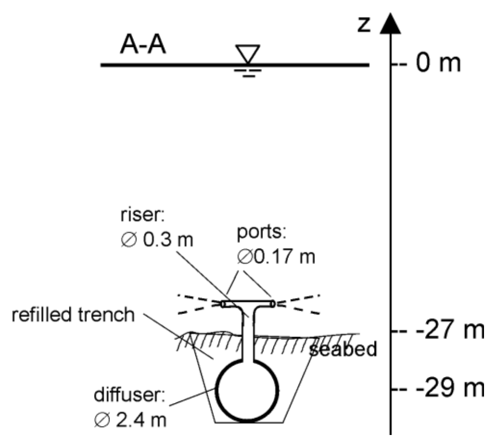
Rio de Janeiro, Brazil, 4 km, concrete



Antalya, Turkey, 2.6 km, HDPE

Boston, USA, 16 km, tunnel


headworks
∅ 2.4 m
ρ
a
A
A
0 m
3877 m
4326 m
x

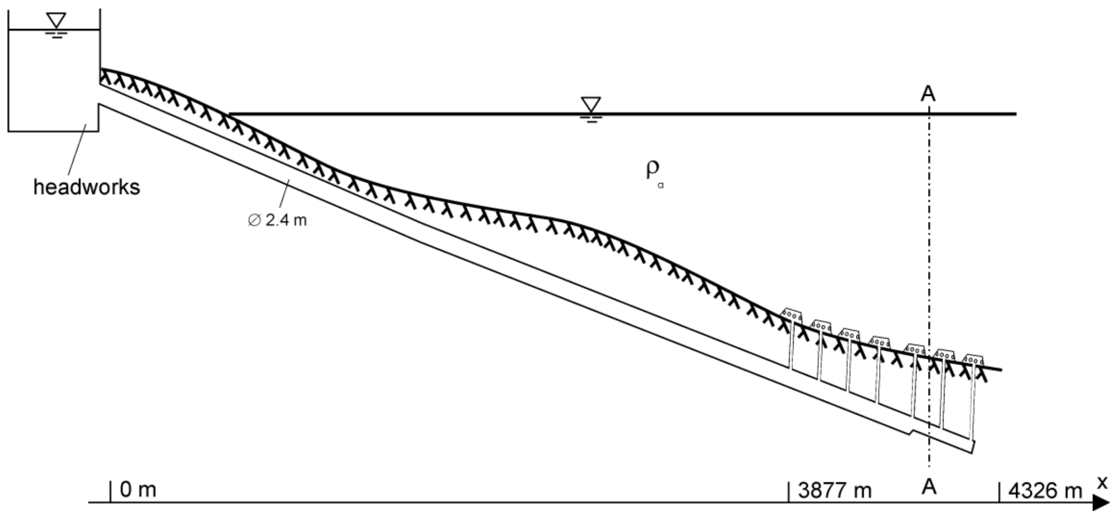

A-A
z
0 m
riser:
∅ 0.3 m
ports:
∅0.17 m
refilled trench
seabed
-27 m
-29 m
diffuser:
∅ 2.4 m

Valdelentisco SWRO (200,000 m^3/d)

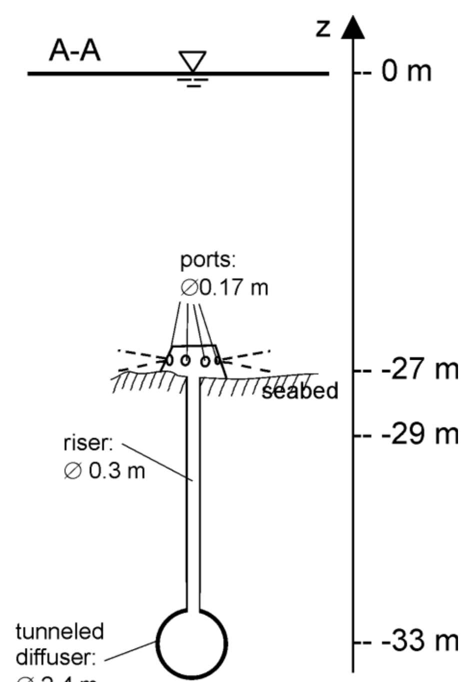
- submerged outfall
  - water depth: −22 m
  - diffuser system

Latorre et al. 2007

Latorre et al. 2007

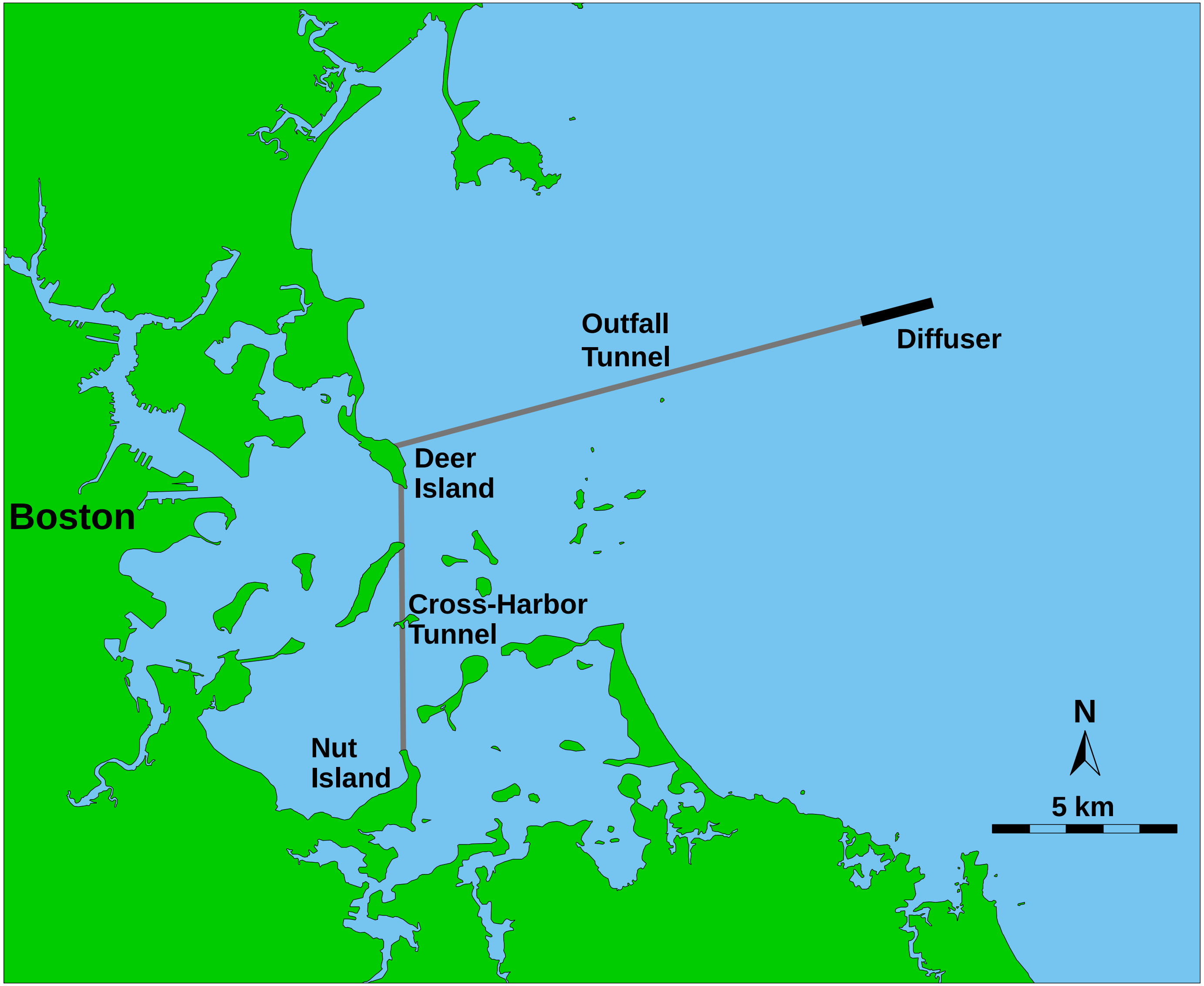


headworks
∅ 2.4 m
ρ
A
A
0 m
3877 m
4326 m
x

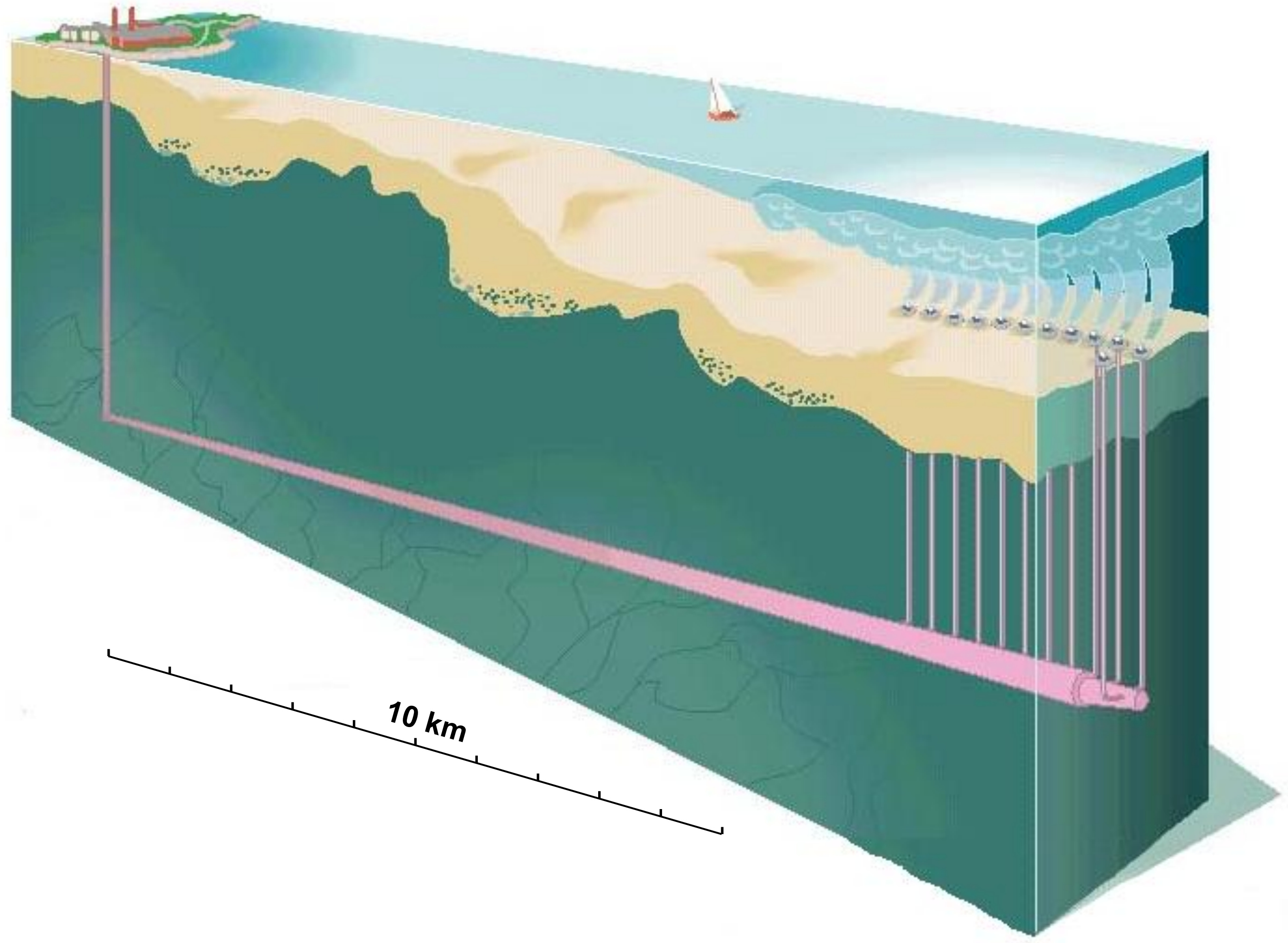


A-A
z
0 m
ports:
∅0.17 m
-27 m
seabed
-29 m
riser:
∅ 0.3 m
tunneled
diffuser:
∅ 2.4 m
-33 m

Schematic of Boston Harbor Wastewater Project

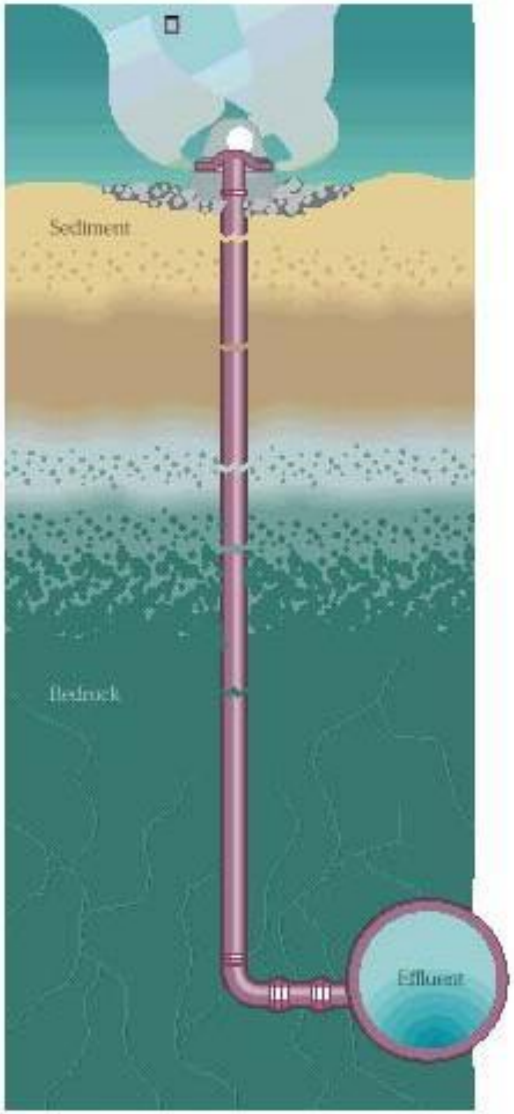


Boston Harbor Wastewater Project



Inside the Outfall Tunnel

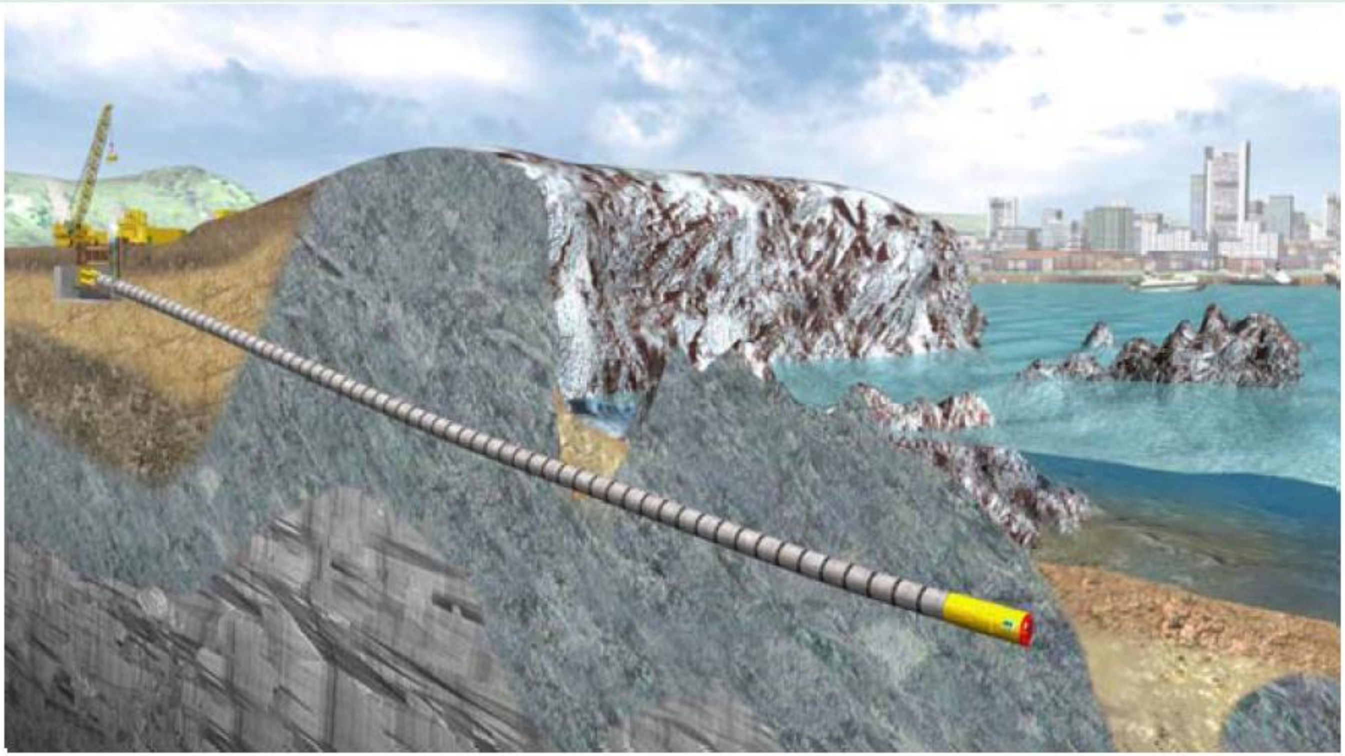
How Many Risers?



Boston Outfall Riser Cap

How Many Risers?

HERRENKNECHT AG | UTILITY TUNNELLING | TRAFFIC TUNNELLING



HERRENKNECHT AG.

Recovery of Microtunnelling Machines in the Sea without Shaft at Intakes and Sea Outfalls

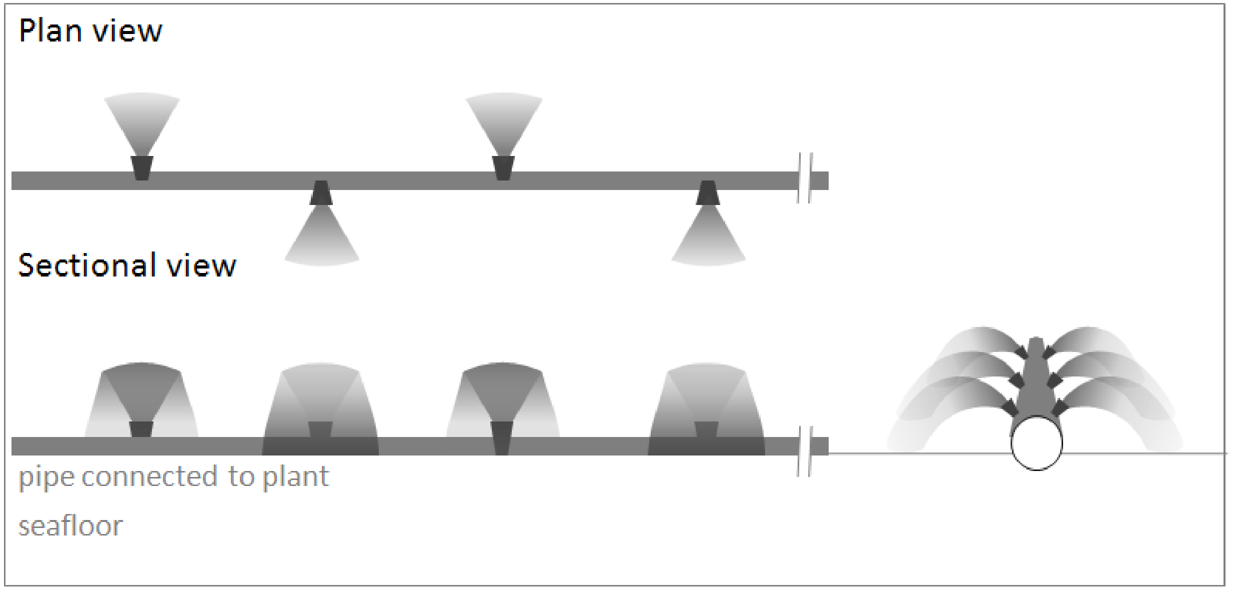
Lutz zur Linde

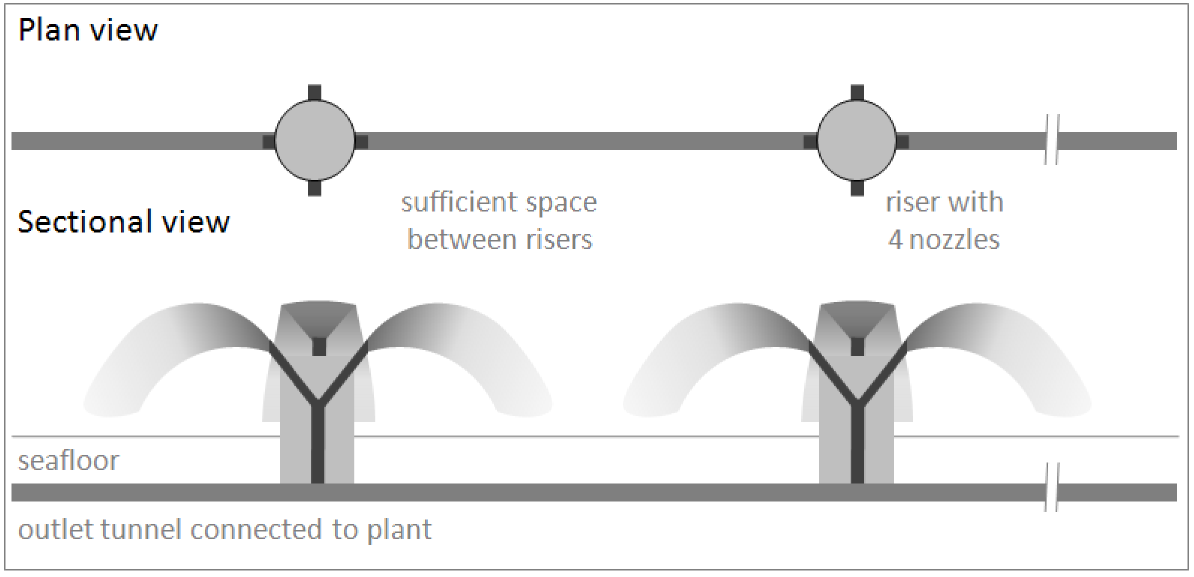
HERRENKNECHT
Tunnelvortriebstechnik

Sea Outfall SANTOS Brasil

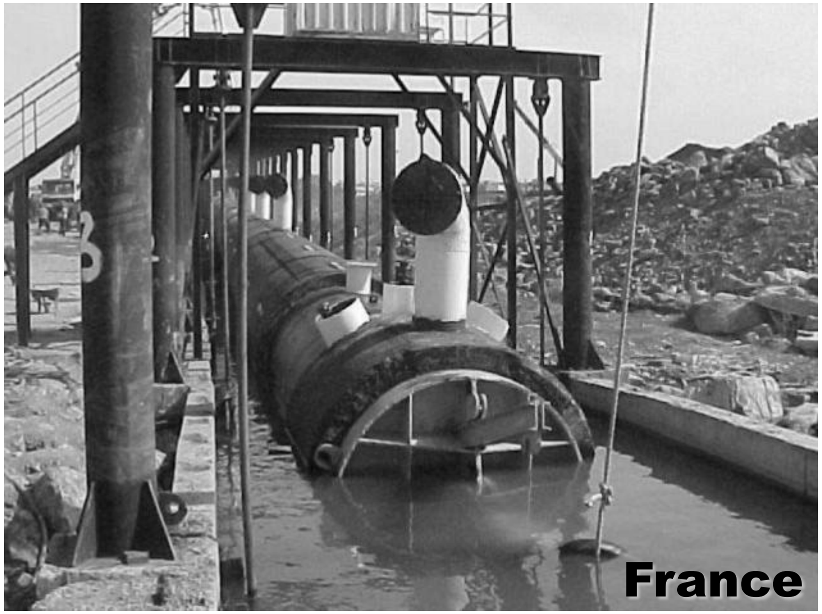
SANTOS Brasil, recovery without shaft

Multiport diffusers



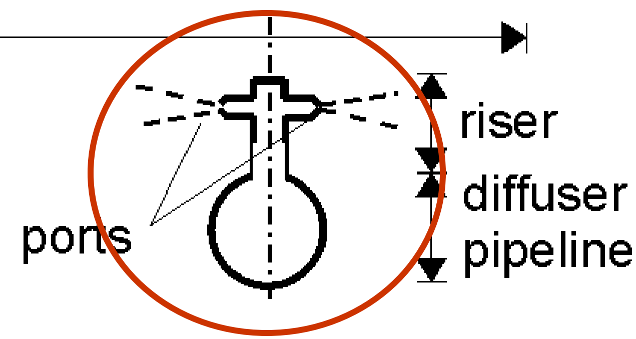


Multiport diffusers

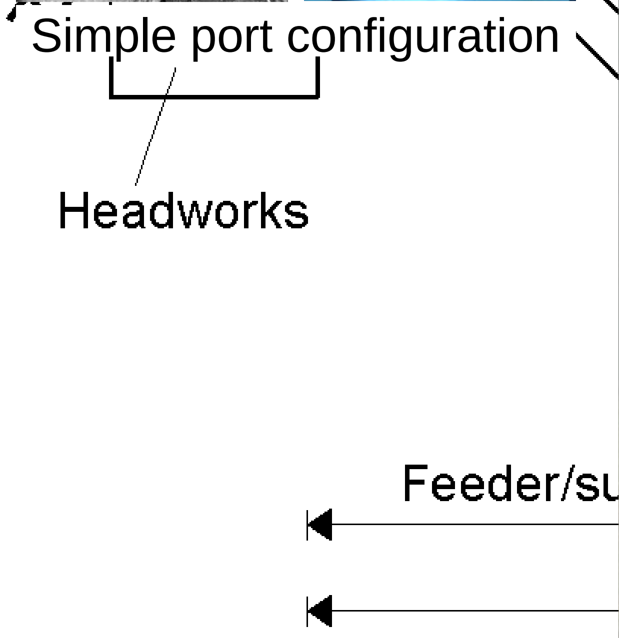


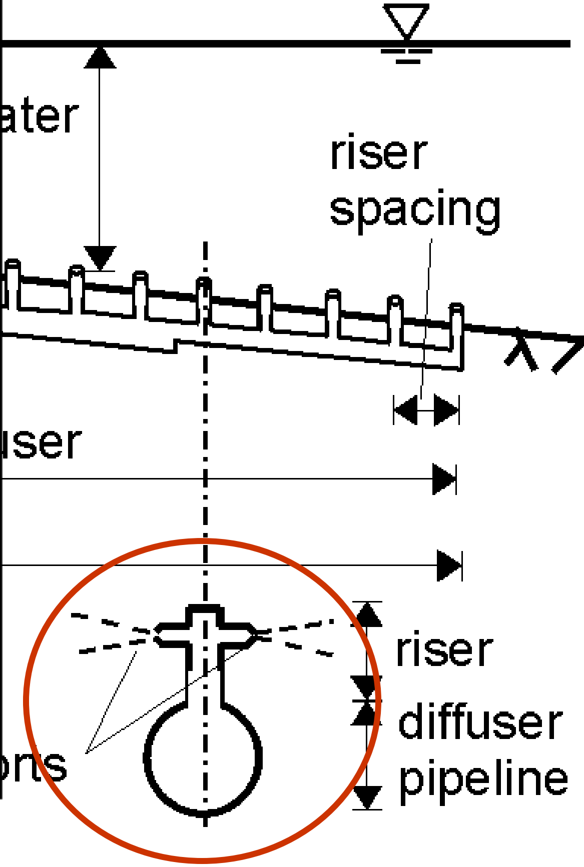
Mixing devices

Simple ports (Source: C. Avanzini, M.E.C.C.)



Mixing devices





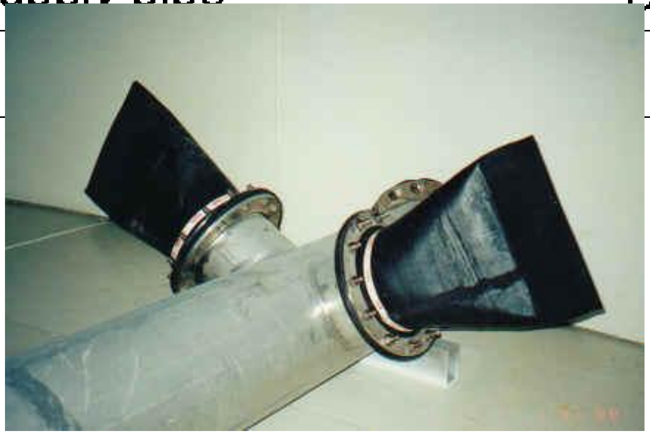
Riser/port configuration (Guarajá outfall, coast of Sao Paulo, Brazil, Source: T. Bleninger)

Mixing devices

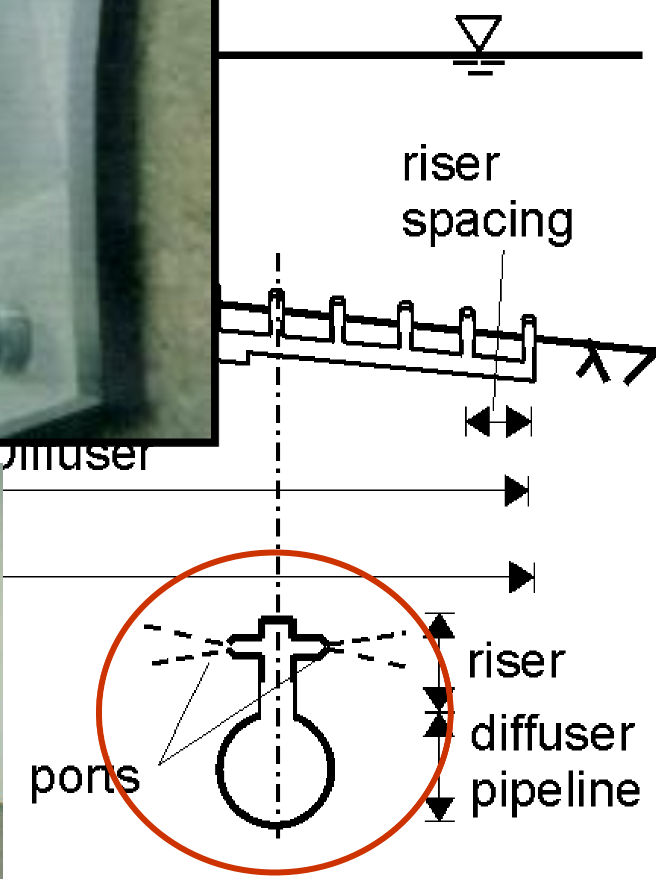
Simple port configuration

Riser / port configuration

Rosette like port arrangement



Duckbill Valves (Source: Red Valve Company)



Mixing processes

Source: Cormix Homepage

Mixing processes

A thermal image of the cooling water multiport diffuser discharge from the Brown's Ferry Nuclear reactor. Source: Cormix Homepage

Mixing processes

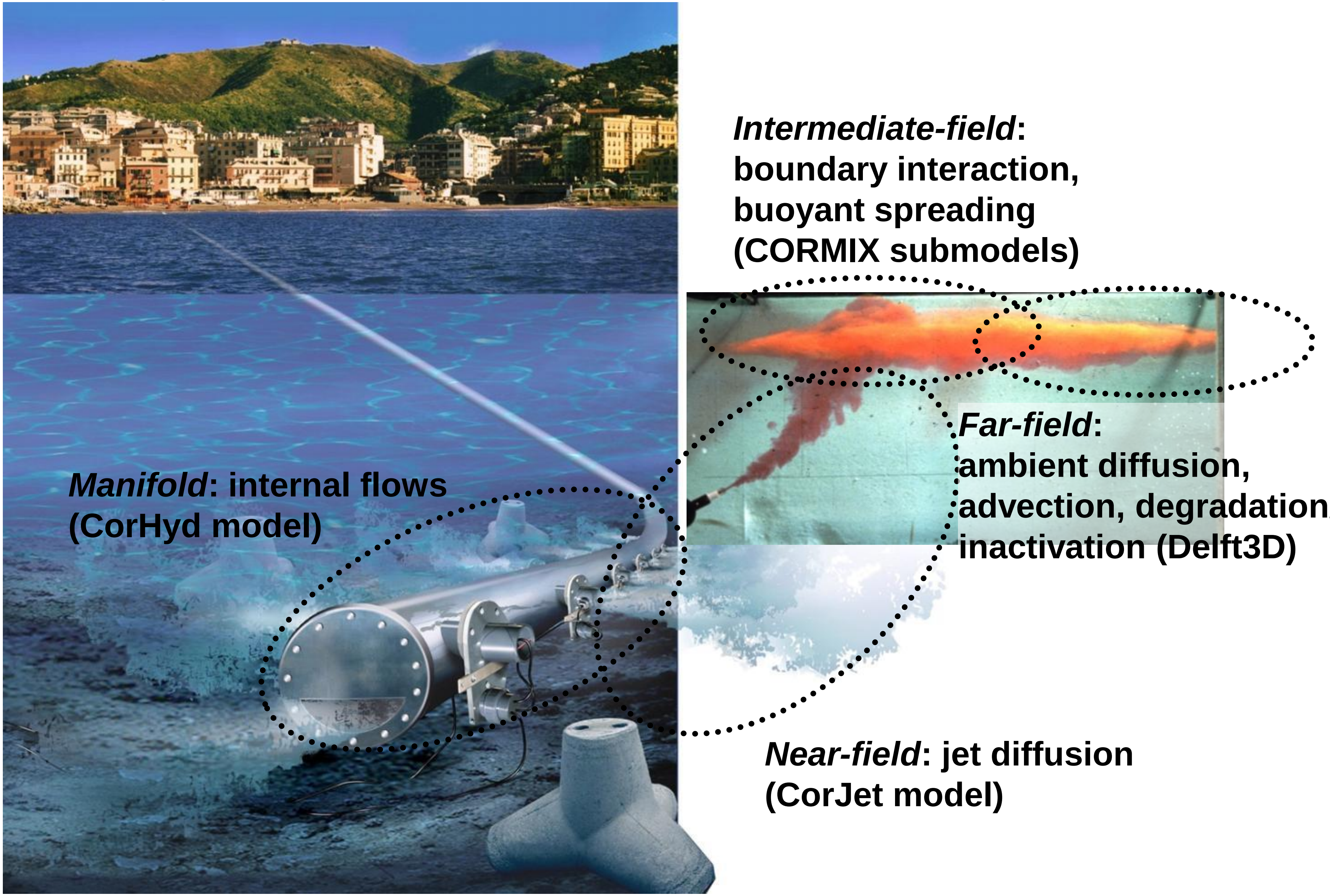
Source: C. Lamparelli, CETESB, Sao Paulo, Brazil

Mixing processes

Source: C. Lamparelli, CETESB, Sao Paulo, Brazil


outfall
Nov. 2003 (peak season!): 78 of 128 beaches declared „not appropriate for bathing“
Santos Bay, Brazil
Source: Prefeitura de Praia Grande, Brazil

Mixing processes



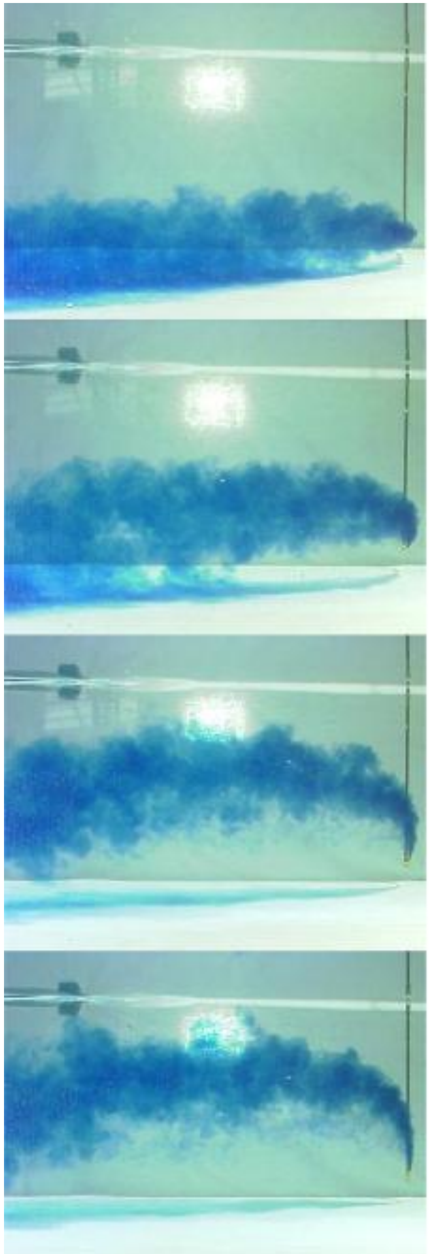
(courtesy of Paolo Domenichini, Italy)

Laboratory visualization: Dense jet with crossflow (side view)

Laboratory visualization:
Dense jet with crossflow (top view)

Laboratory visualization: Dense jet with crossflow

Side view



0°

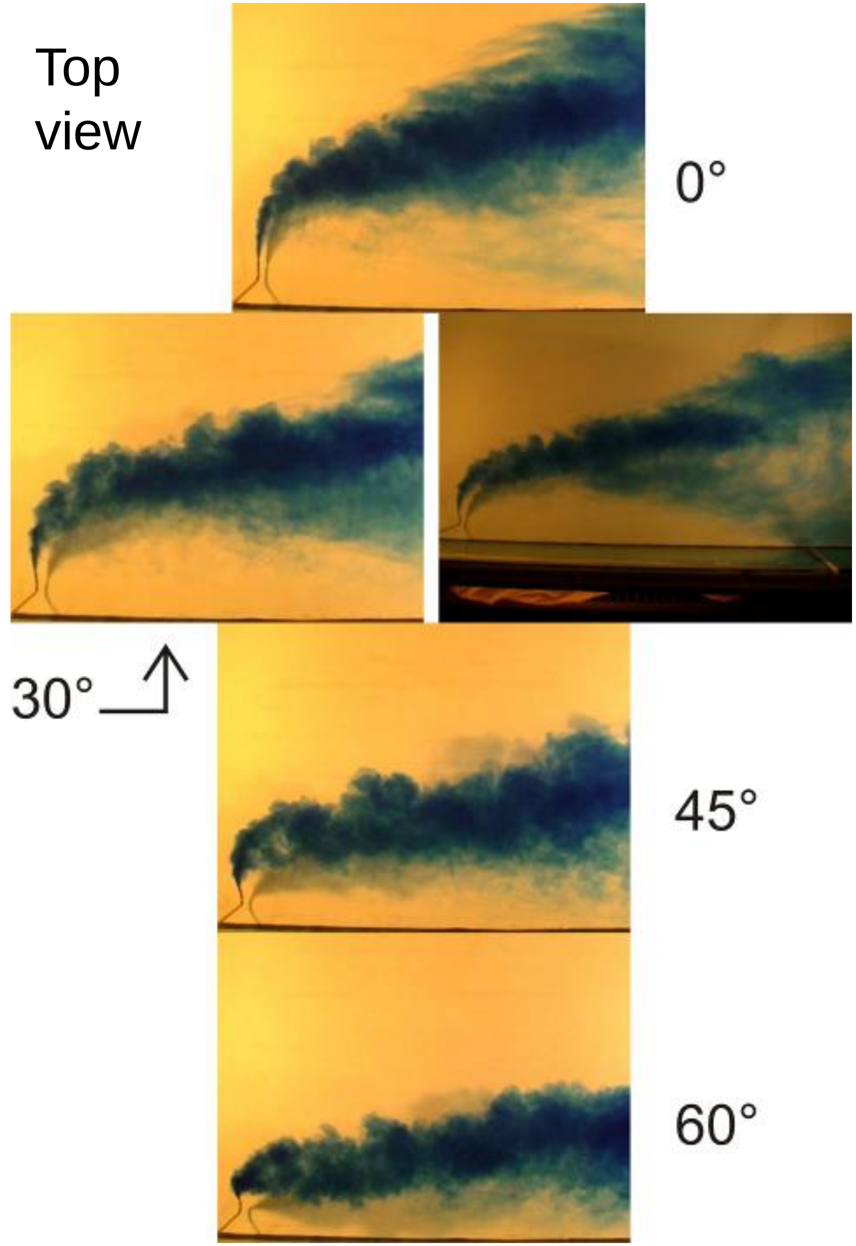
vertical discharge angle

30°

45°

60°

Top view



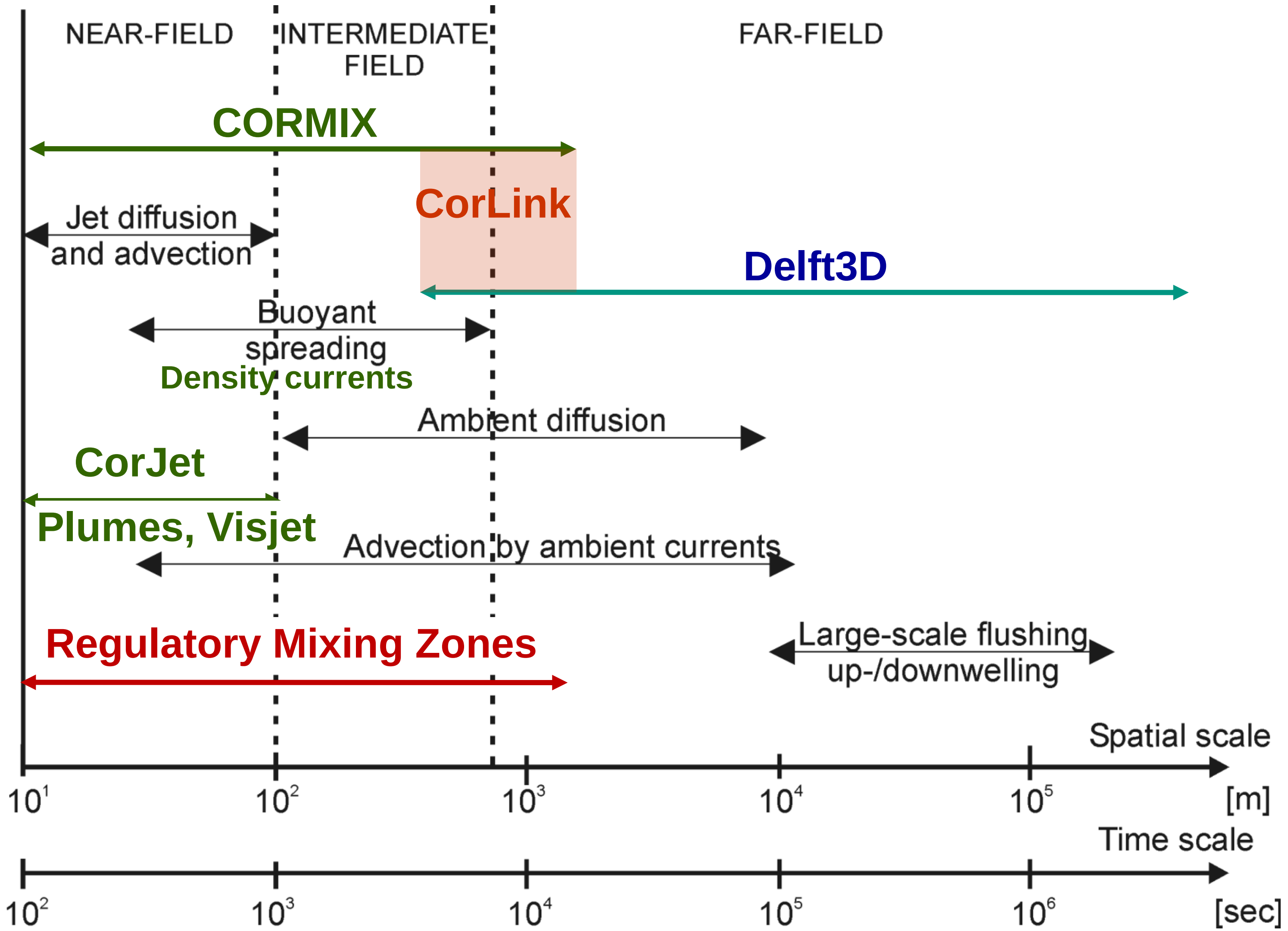
0°

30°

45°

60°

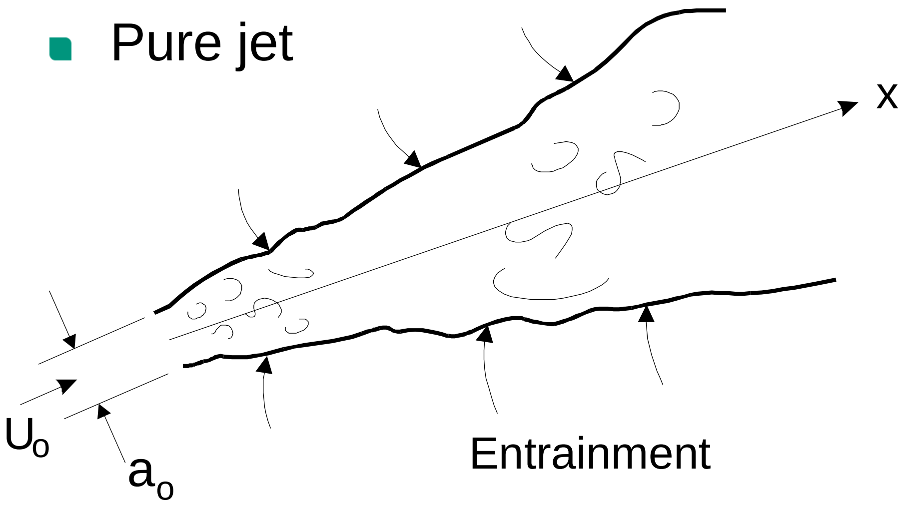
Scale and process differences



(Fischer et. al, 1979; Jirka & Lee, 1994;)

Turbulent buoyant jets and plumes

- Active dispersal through induced turbulence
  - Pure jet



Momentum flux

$$M_o = U_o^2 a_o$$

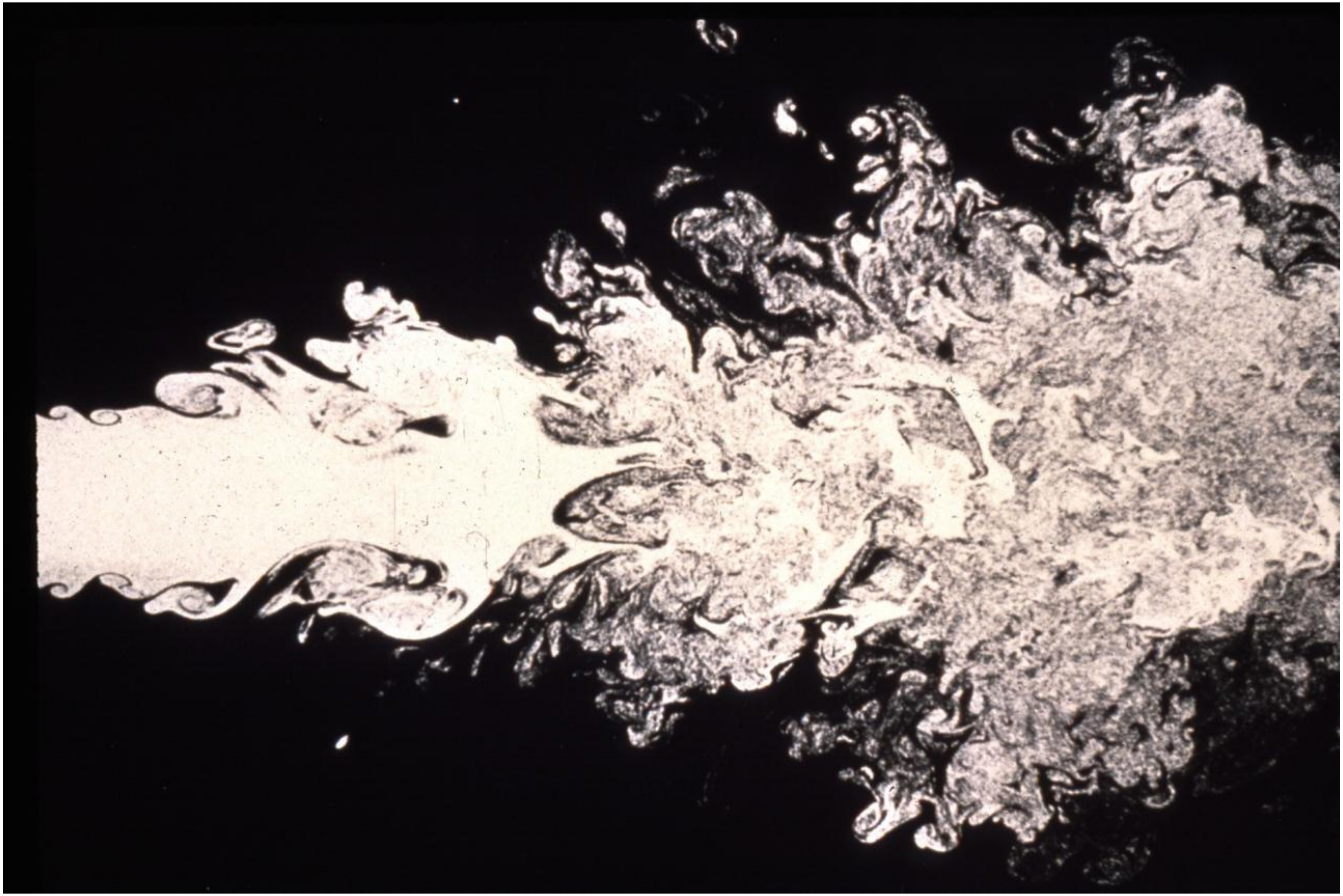
$$a_o = D^2\pi/4$$

$$Q_o = U_o a_o$$

Fully turbulent if $Re = \frac{U_0 D}{\nu} \geq 2000$

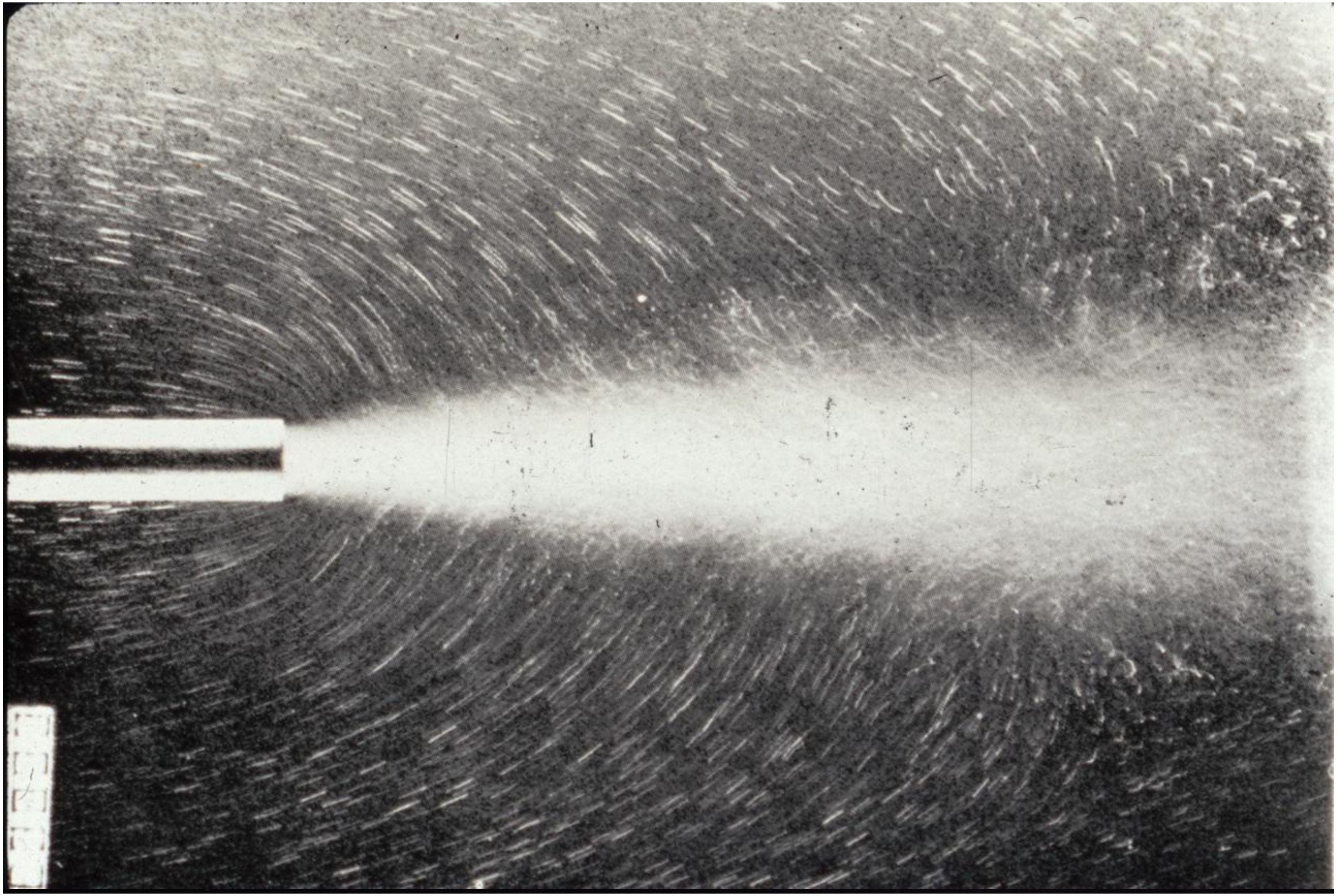
Turbulent buoyant jets and plumes

- Active dispersal through induced turbulence



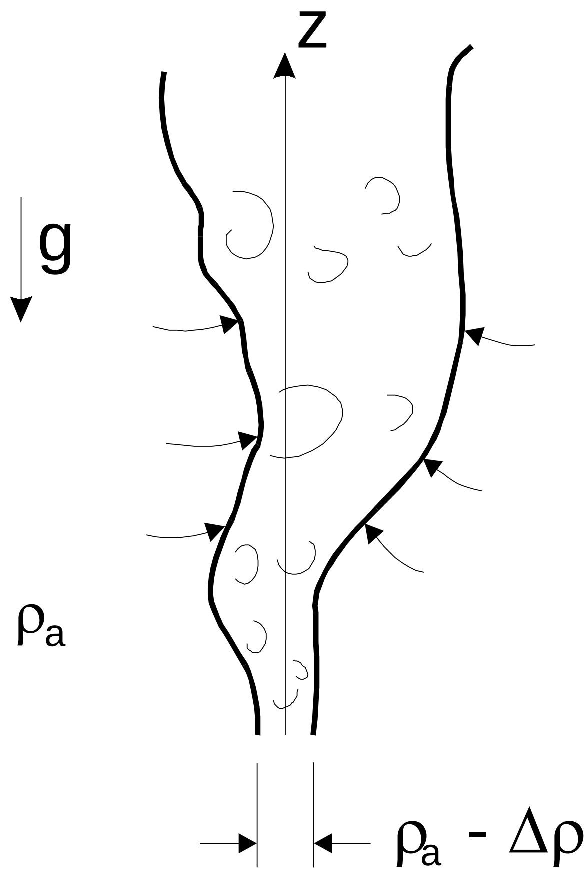
Turbulent buoyant jets and plumes

- Active dispersal through induced turbulence



Turbulent buoyant jets and plumes

- Active dispersal through induced turbulence
  - Pure plume



Buoyancy flux

$$J_o = \left(\frac{\Delta\rho}{\rho_a} g\right) U_o \, a_o$$

$$= g'_o Q_o$$

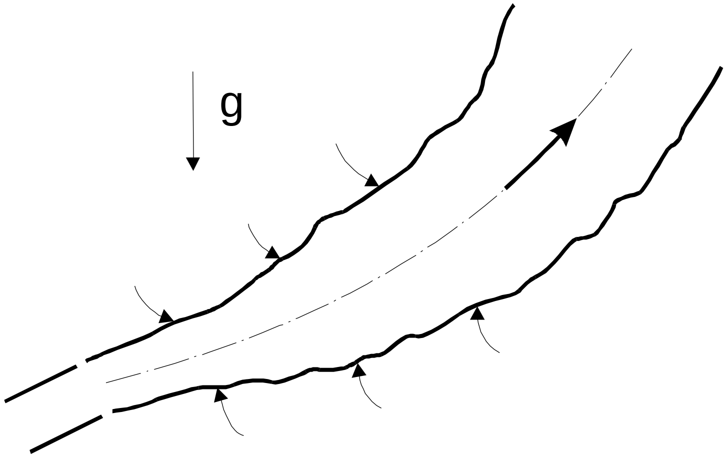
Turbulent buoyant jets and plumes

- Active dispersal through induced turbulence

Turbulent buoyant jets and plumes

Active dispersal through induced turbulence

- Combination:
  buoyant jet or
  forced plume

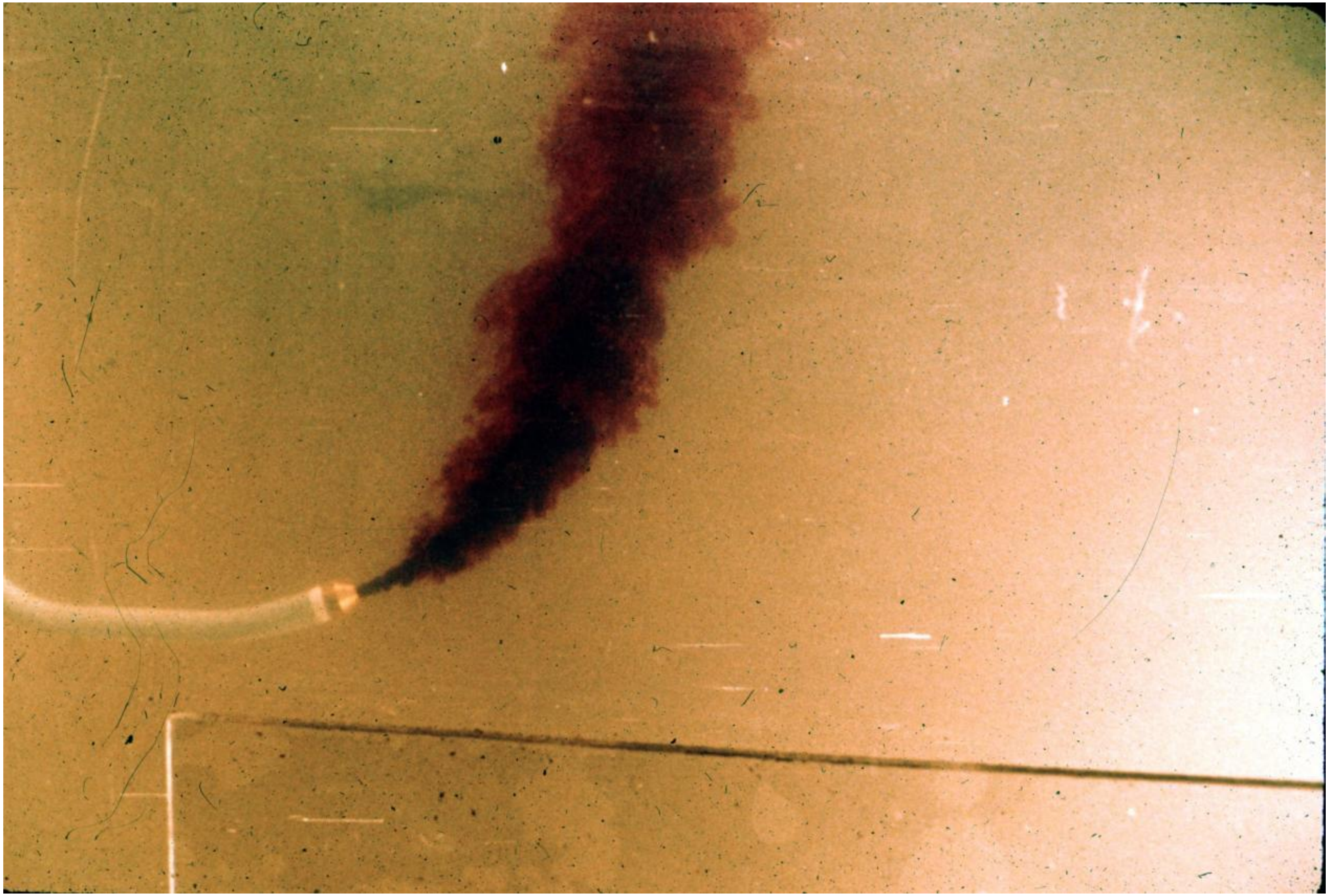


Homogeneous ambient

ρ_a = const.

Turbulent buoyant jets and plumes

Active dispersal through induced turbulence



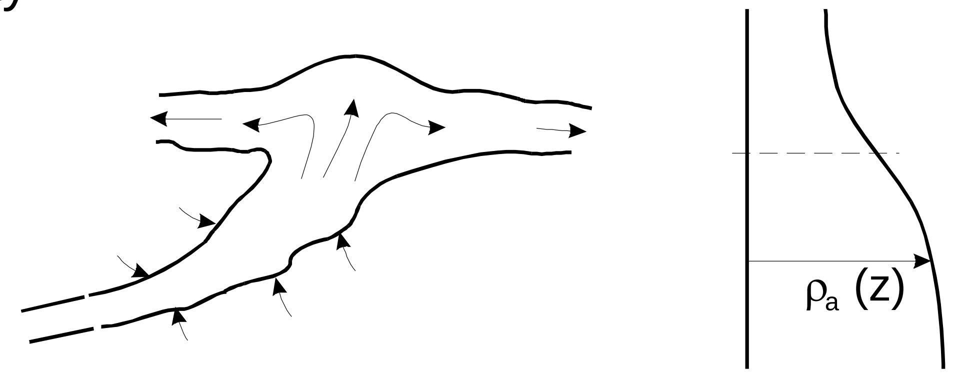
Turbulent buoyant jets and plumes

Active dispersal through induced turbulence

Turbulent buoyant jets and plumes

Active dispersal through induced turbulence

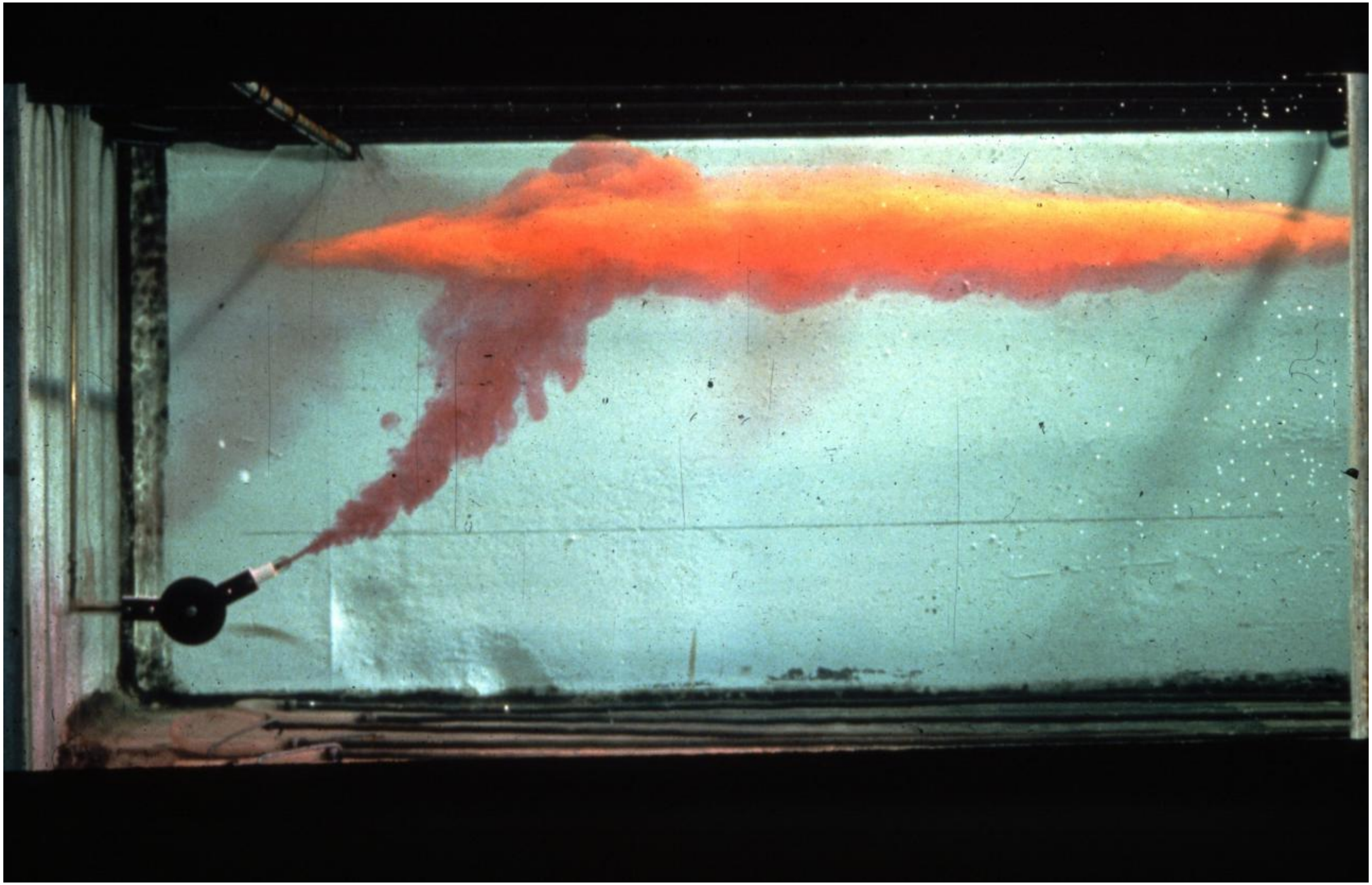
- Ambient density stratification



$$\frac{\partial \rho_a}{\partial z} < 0$$

Turbulent buoyant jets and plumes

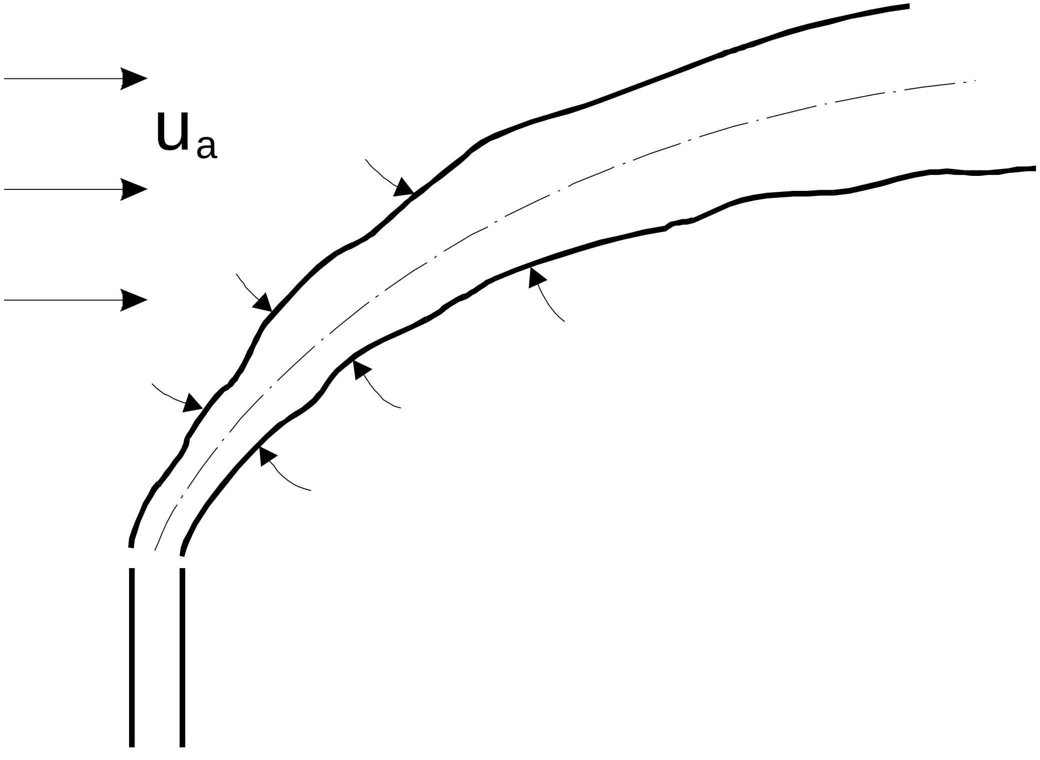
Active dispersal through induced turbulence



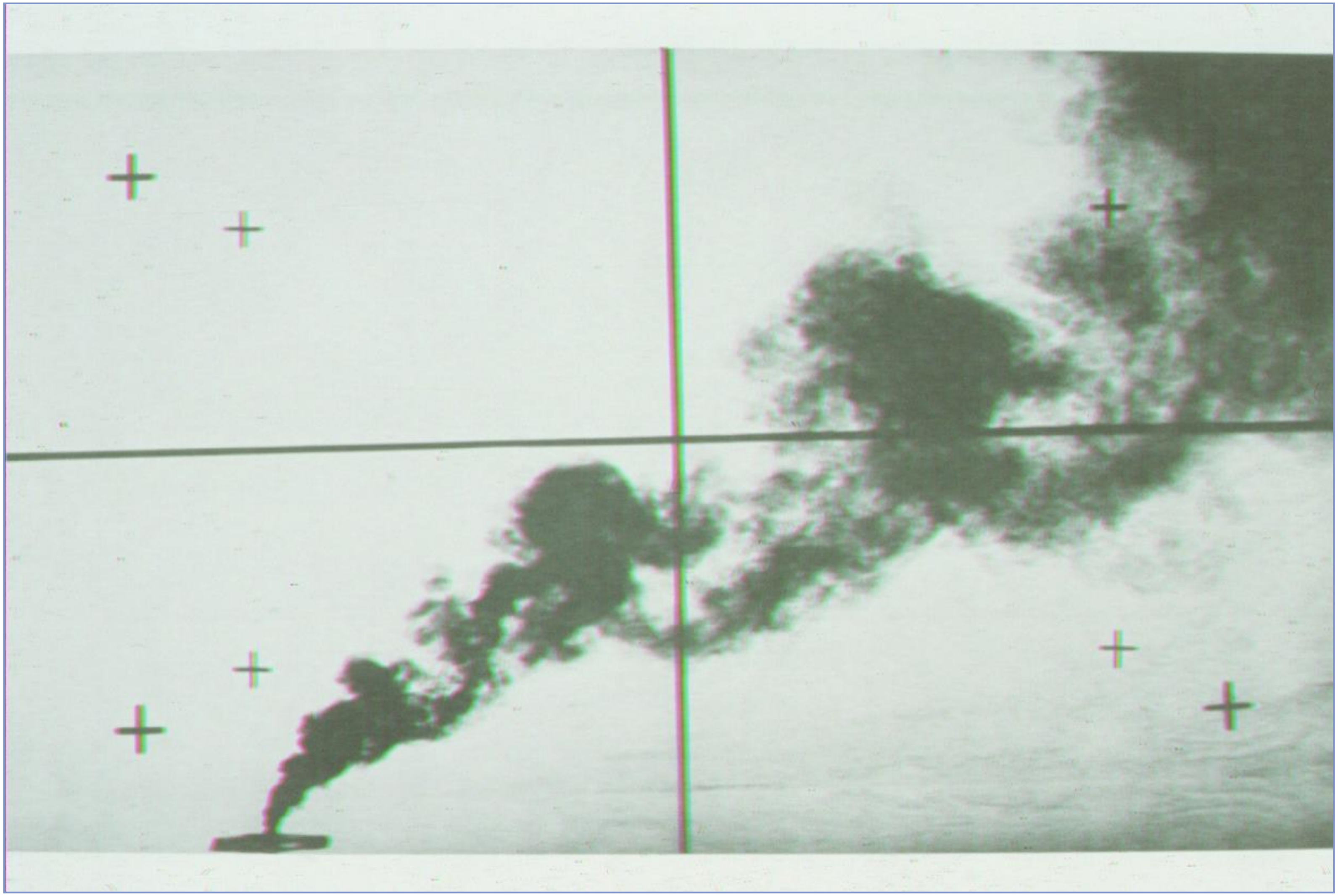
Turbulent buoyant jets and plumes

Active dispersal through induced turbulence

- Ambient crossflow

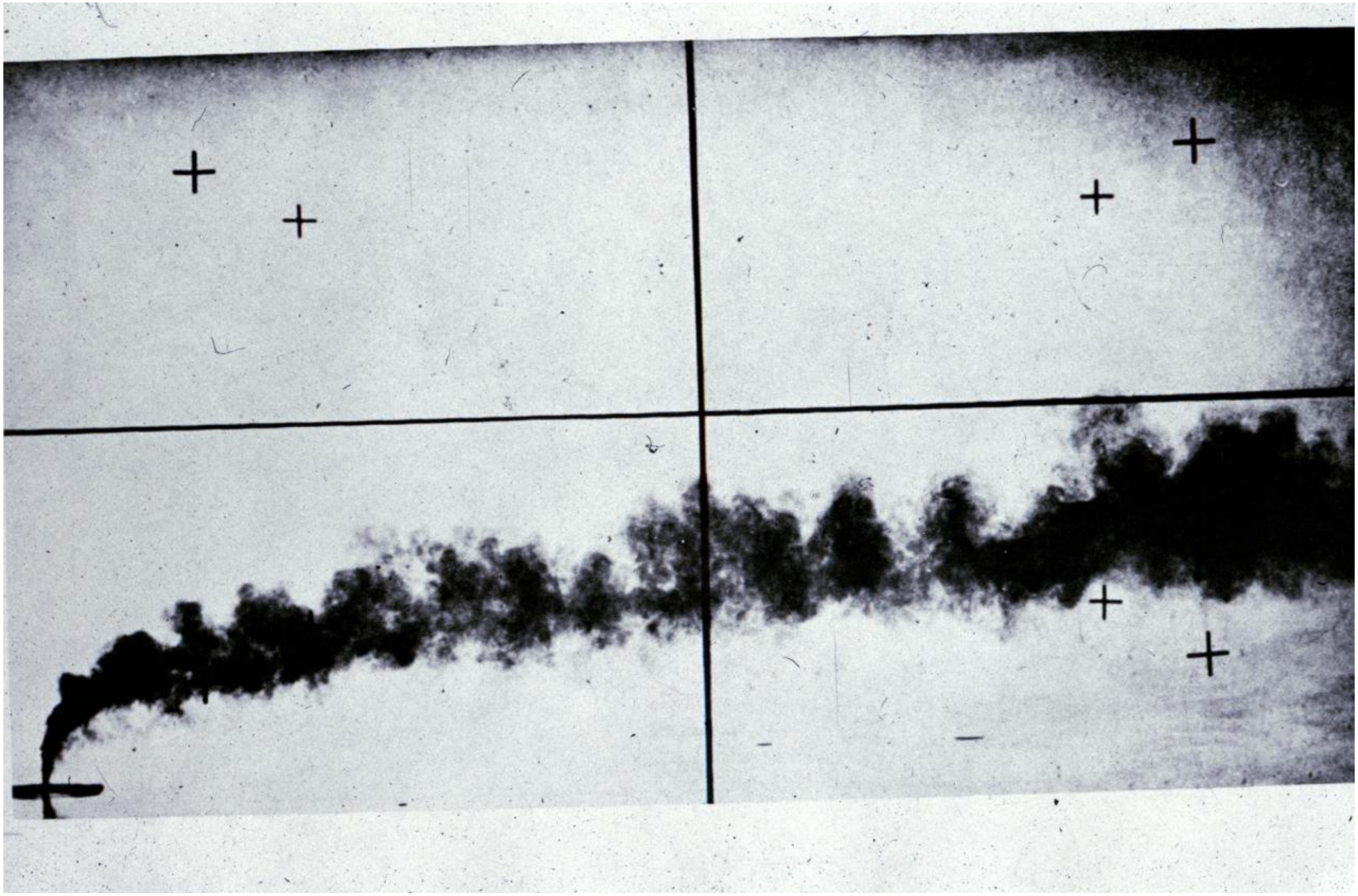


Mixing Example



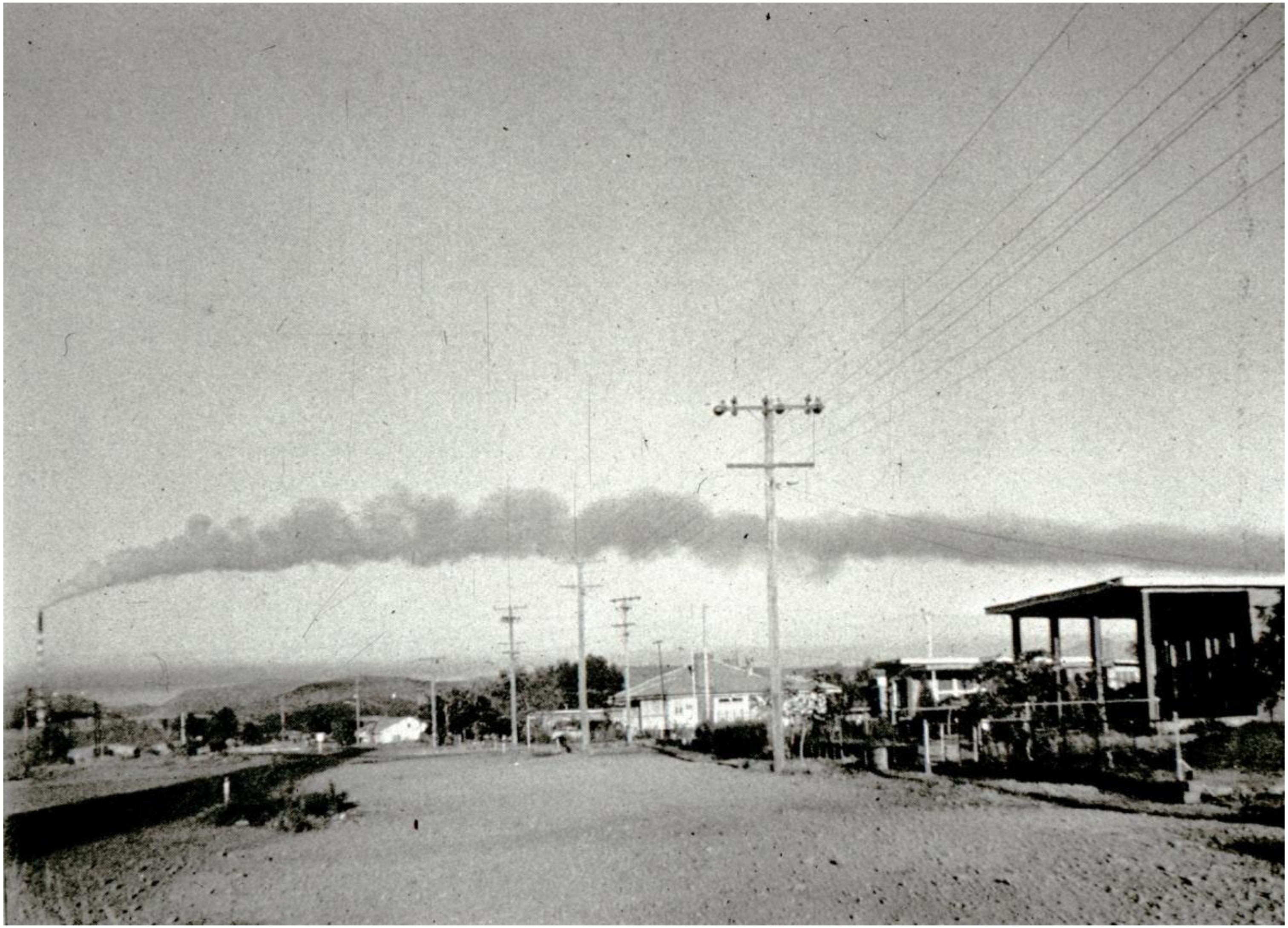
Turbulent buoyant jets and plumes

Active dispersal through induced turbulence



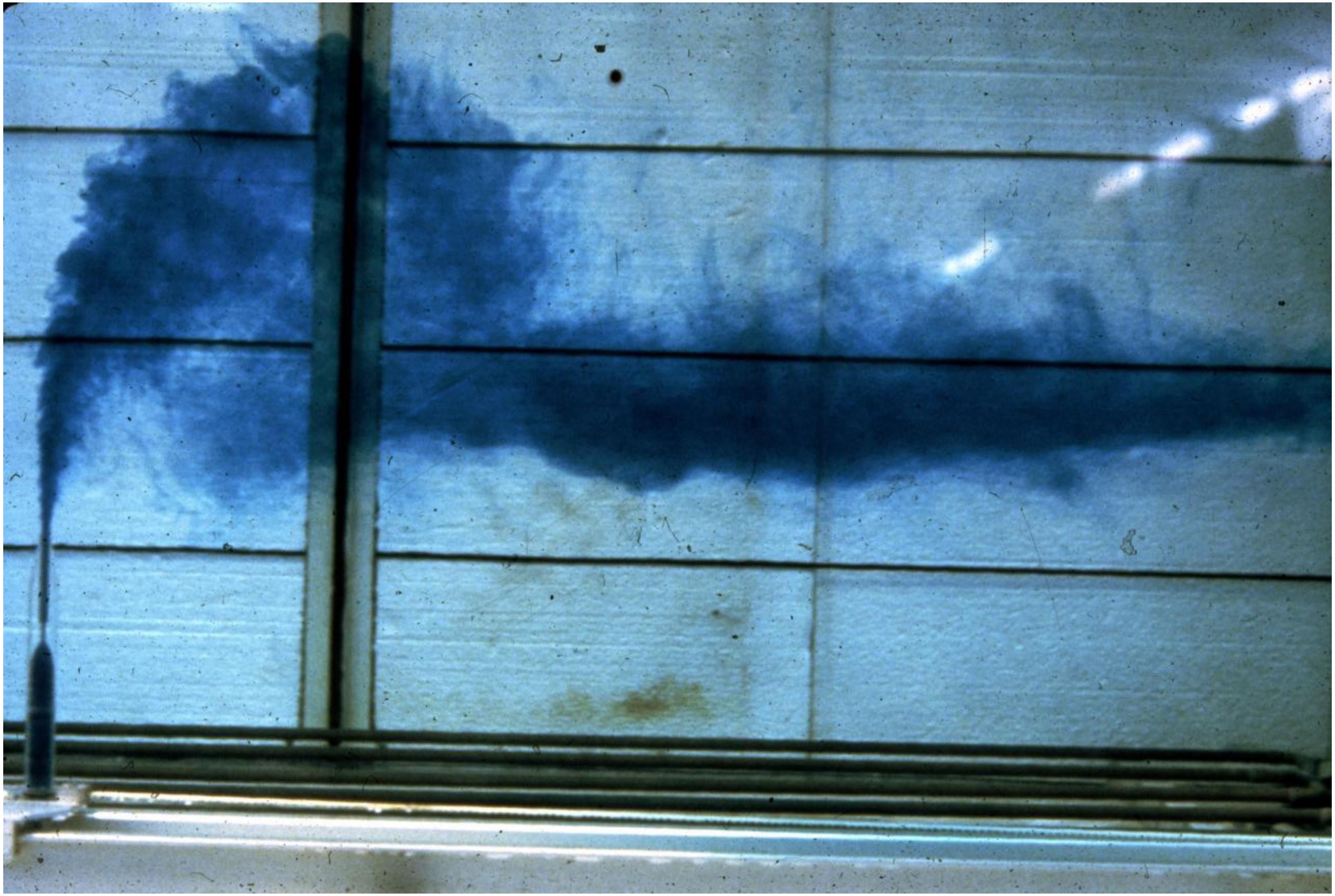
Turbulent buoyant jets and plumes

Active dispersal through induced turbulence

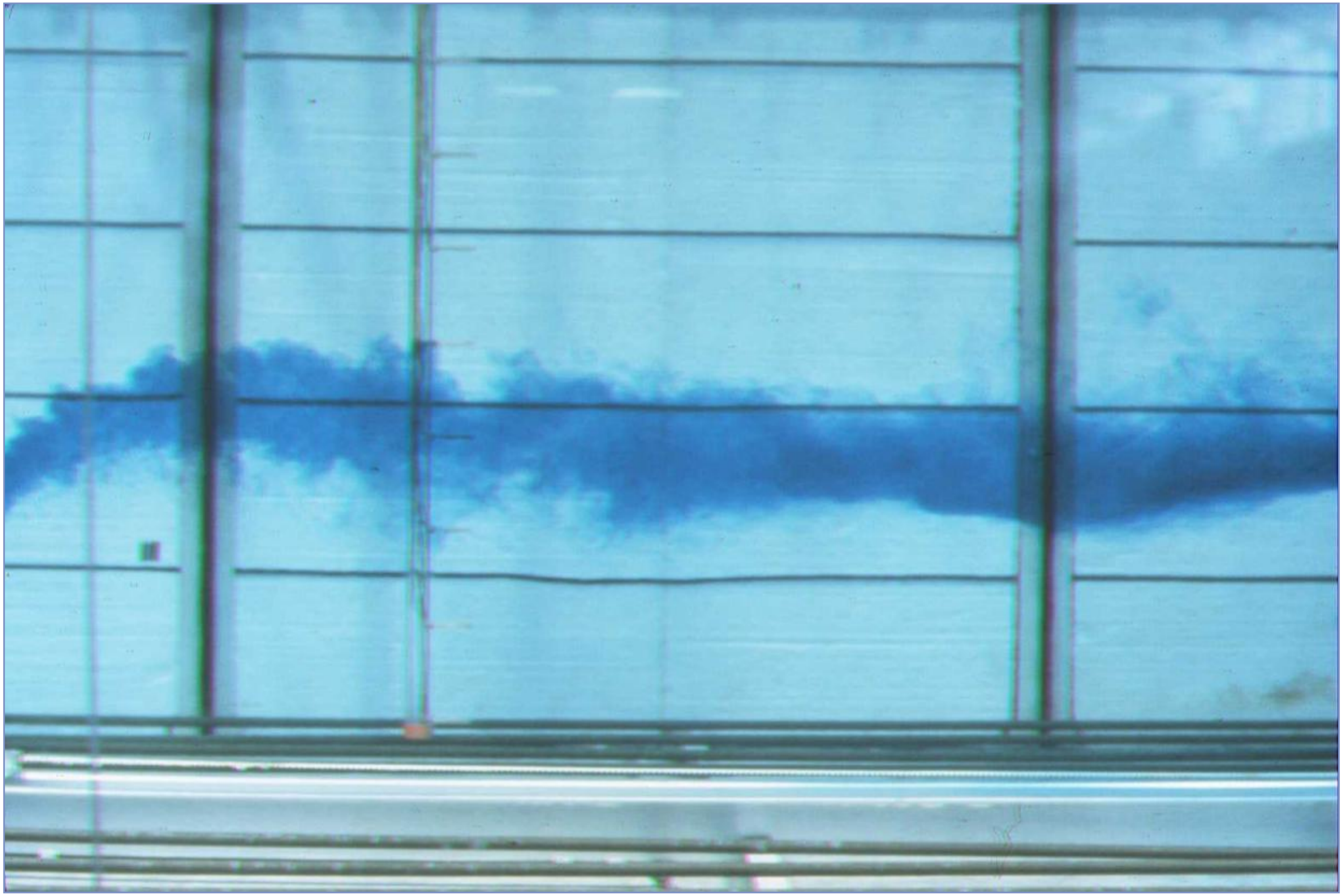


Turbulent buoyant jets and plumes

Active dispersal through induced turbulence

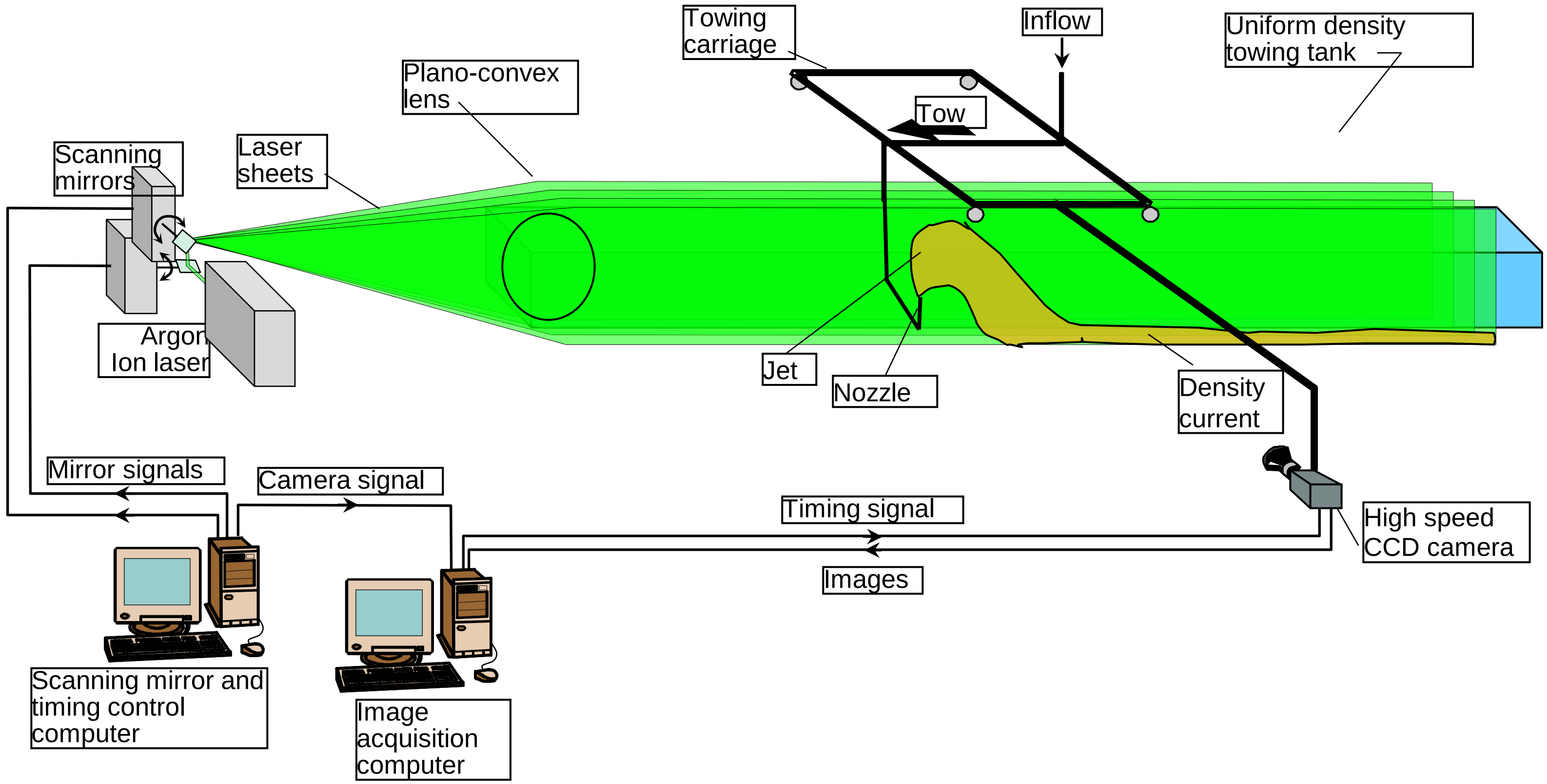


Mixing Example



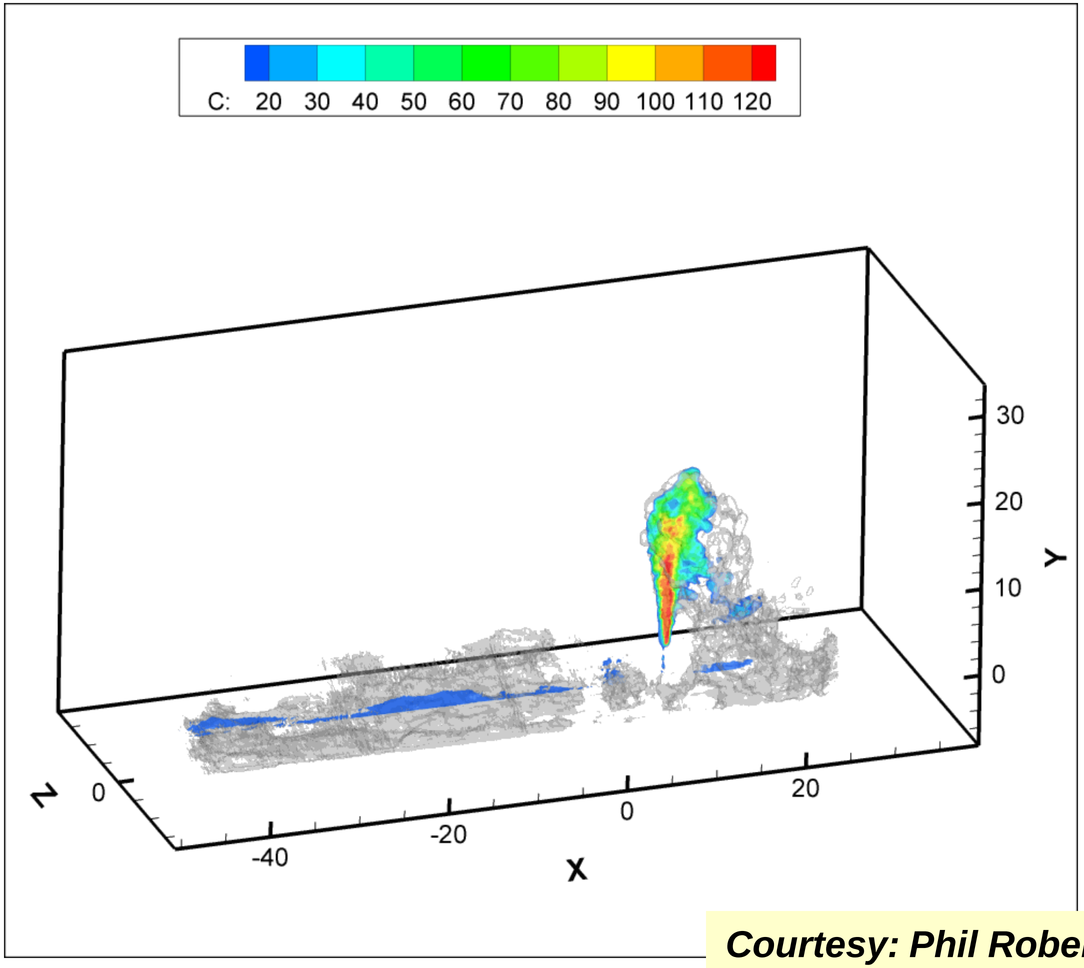
Mixing Example

3D Laser-Induced Fluorescence Experiments



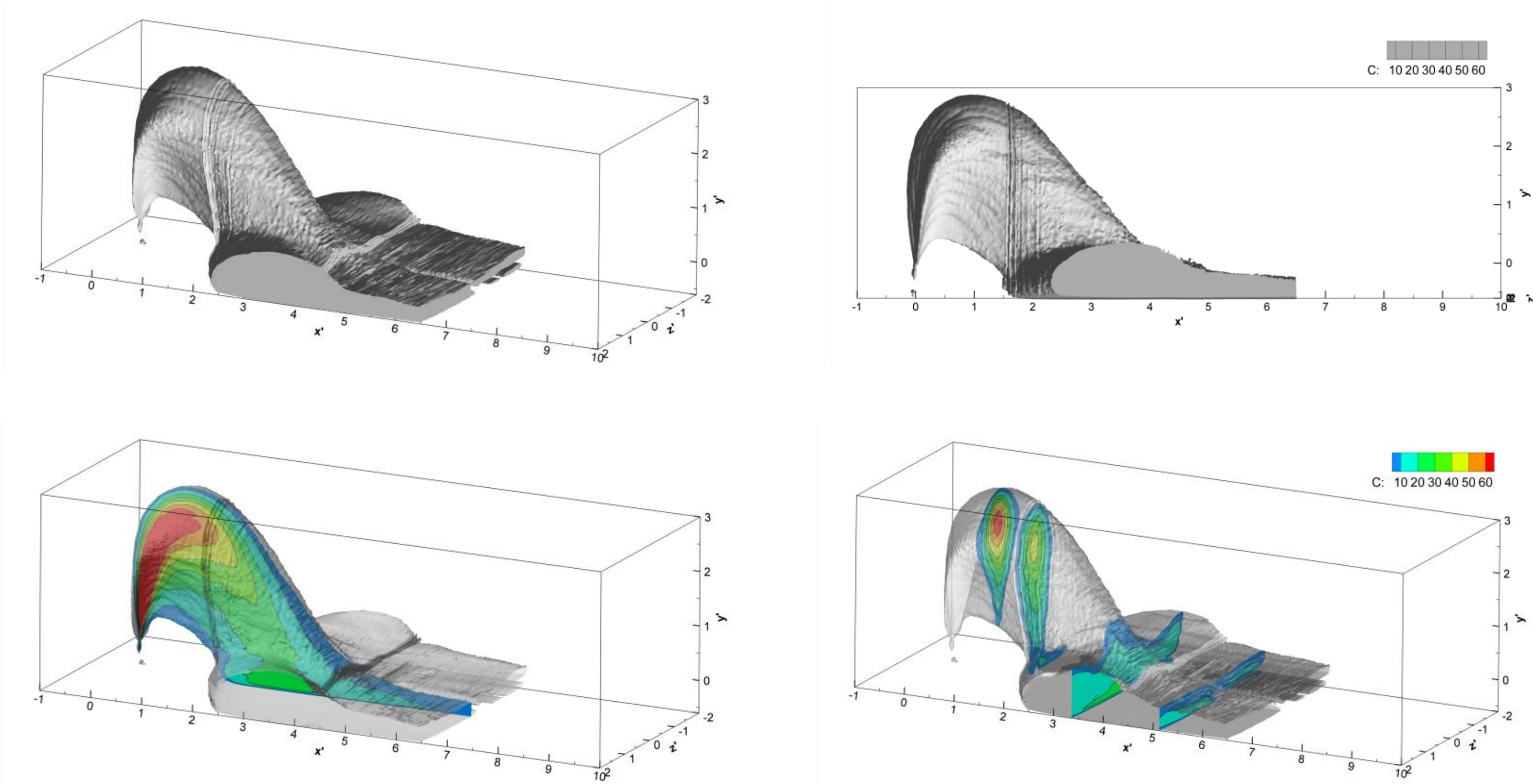
Courtesy: Phil Roberts, Georgia Tech

Flow Animations



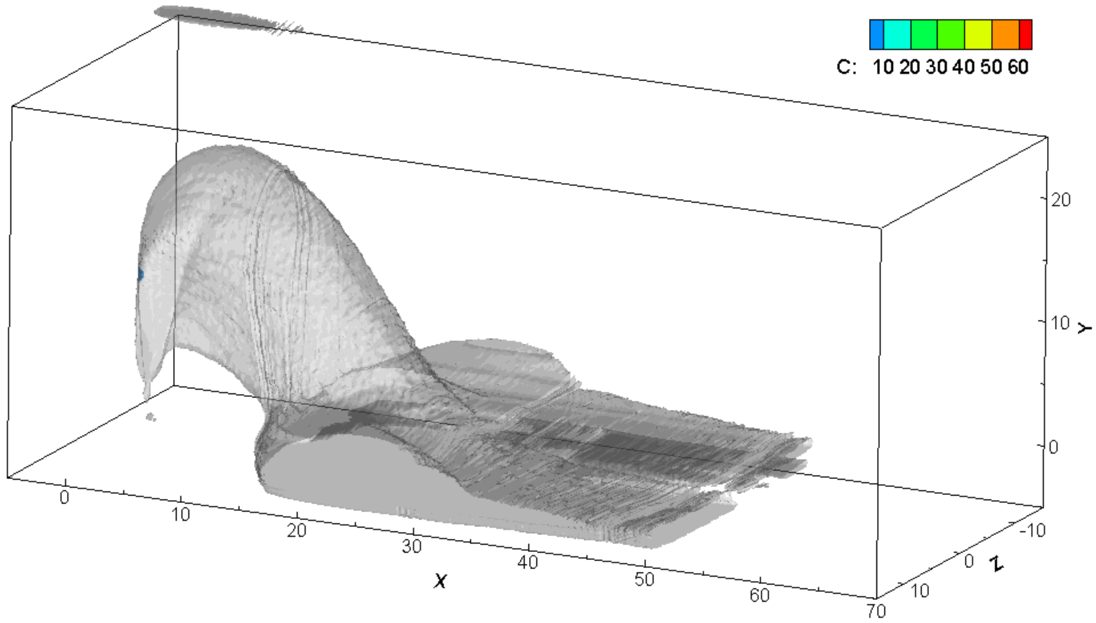
Courtesy: Phil Roberts, Georgia Tech

Results



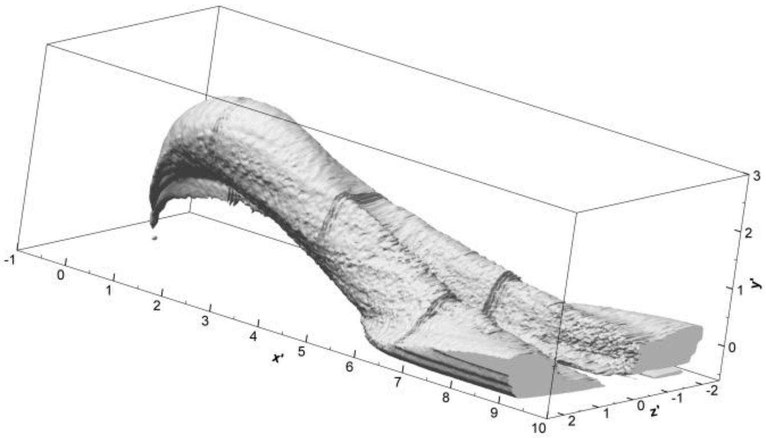
Courtesy: Phil Roberts, Georgia Tech

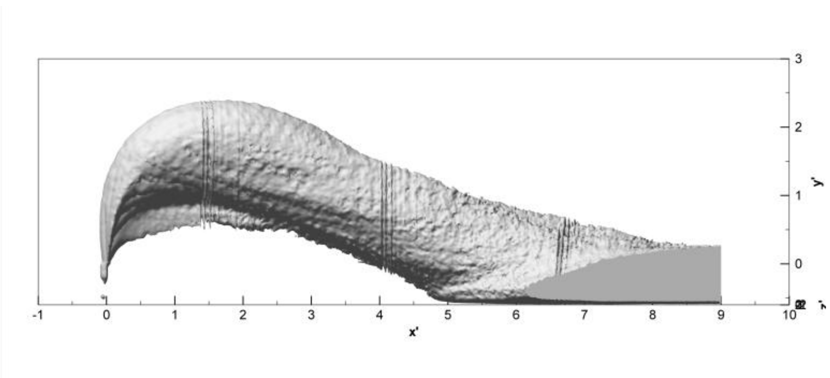
Animation of Lateral Profiles

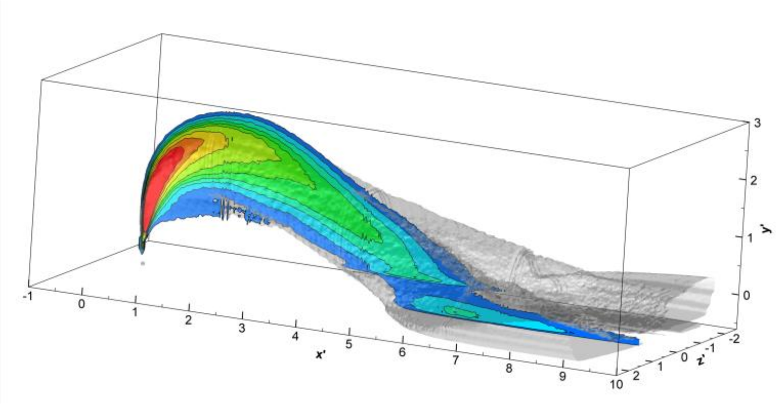


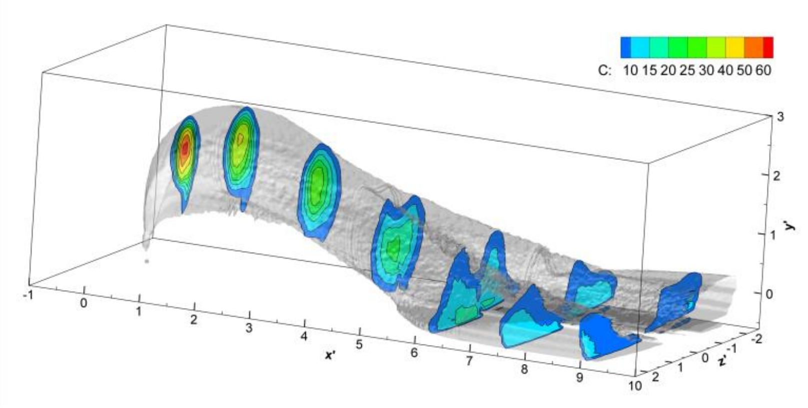
Courtesy: Phil Roberts, Georgia Tech

Results



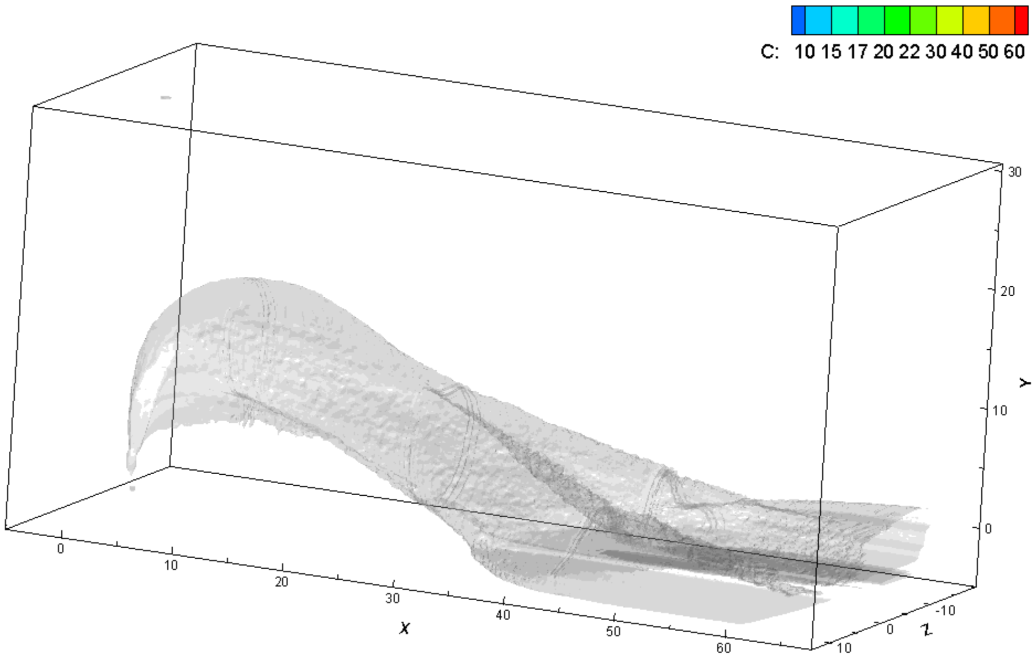






Courtesy: Phil Roberts, Georgia Tech

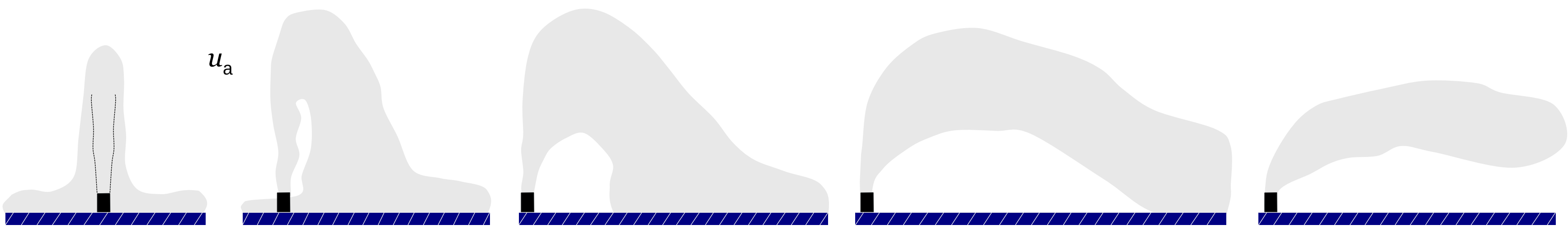
Animation of Lateral Profiles



Courtesy: Phil Roberts, Georgia Tech

Vertical Dense Jet in Crossflow

Flow characteristics for various values of u_rF



u_rF = 0
Falls back

u_rF ≈ 0.2
Slight deflection, upstream wedge

u_rF ≈ 0.5
No upstream wedge, maximum rise height

u_rF ≈ 1
Significantly bent

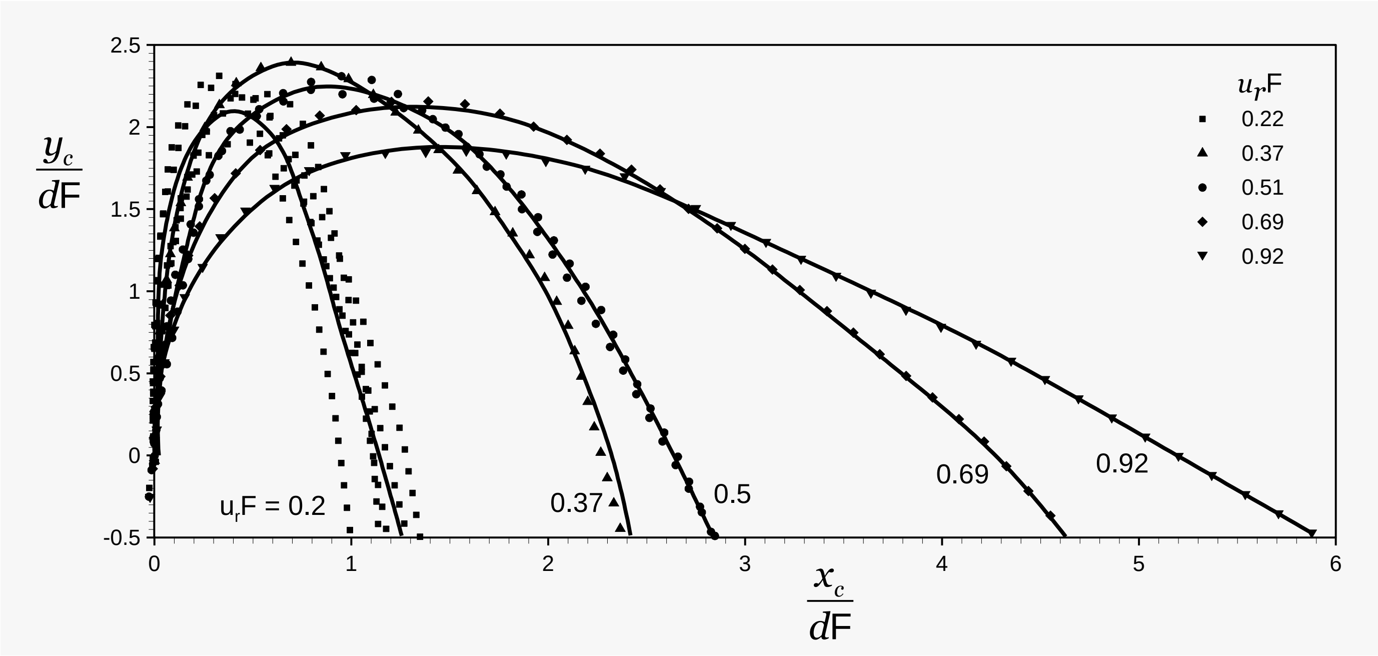
u_rF ≈ 2
Almost horizontal

Densimetric Froude number: $$\mathrm{F} = \frac{u}{\sqrt{g_o' d}}$$

Current speed parameter: $$u_r\mathrm{F} = \frac{u_a}{u}\mathrm{F}$$

Courtesy: Phil Roberts, Georgia Tech

Quantitative Results

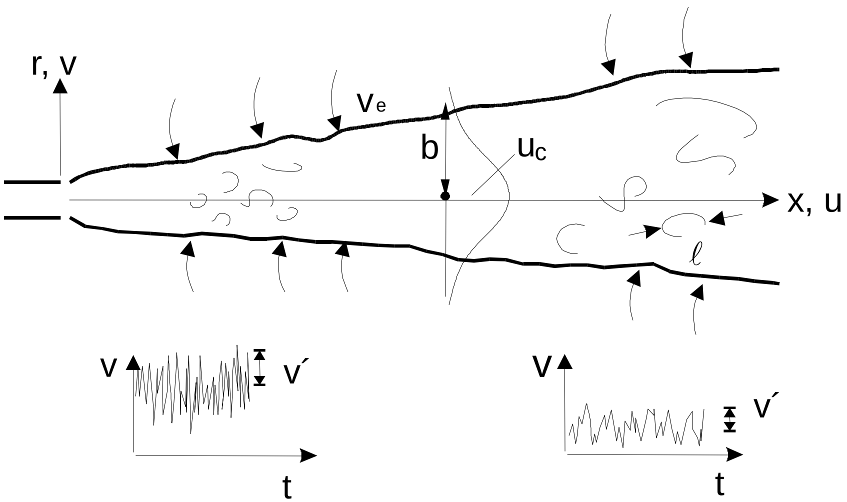


Courtesy: Phil Roberts, Georgia Tech

Turbulent buoyant jets and plumes

Fundamentals: “FREE TURBULENCE” (Prandtl, Tollmien, Taylor ...)

- Jet:



Mean:
b = jet width
u_c = centerline velocity

Turbulence

ℓ = integral length scale

v´ = integral velocity scale

(r.m.s.)

1. Invariance $\frac{\ell}{b} = \text{const.}$ (≈ 0.3)

2. Erosion = growth rate $\frac{Db}{Dt} \cong u_c \qquad \frac{db}{dx} \sim v'$

3. Prandtl´s approach (mixing length) $v' = \text{const.} \qquad \ell \frac{\partial u}{\partial r} \sim \ell \frac{u_c}{b}$

Turbulent buoyant jets and plumes

Fundamentals: "FREE TURBULENCE"

$$u_c \frac{db}{dx} \sim \ell \frac{u_c}{b} \sim const.u_c$$

$\rightarrow$ $\frac{db}{dx} = k$ — linear spreading — „Jet diffusion“ — spreading of zone containing momentum (and mass)

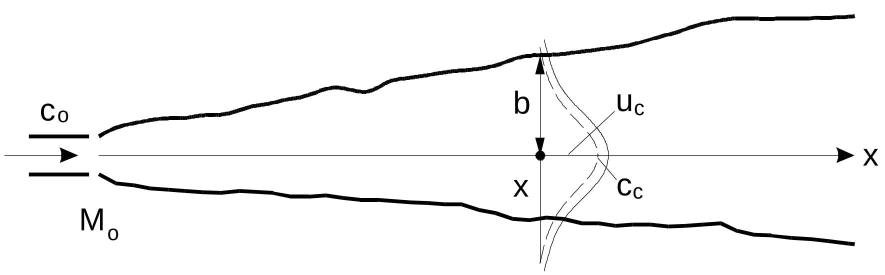
$\frac{v'}{u_c} = const.$ — constant turbulent Intensity

$\rightarrow$ $\frac{v_e}{u_c} = \alpha$ — constant entrainment rate — „Jet entrainment“ — suction of outside fluid into zone (dilution)

Dimensional Analysis of Dynamic jet properties:

$$u_c = g(x, M_o, a_o, \nu ...) \qquad M_o = \left[\frac{L^4}{T^2}\right]$$

$$\frac{b}{x} = const., \qquad \frac{u_c x}{\sqrt{M_o}} = const., \qquad \rightarrow$$



Experiment: $b = 0.10\ x$, $u_c / U_o = 7.1 / (x / D)$

Dimensional analysis

- Simple Jet

Passive properties:

$$Q_{C_o} = c_o U_o a_o \cong c_c u_c b^2$$ Mass flux conserved

$$\frac{c_c}{c_o} \sim \frac{U_o a_o}{u_c b^2} = \frac{1}{\overline{\overline{K}}} \frac{\sqrt{a_o}}{x}$$

Dilution

$$S = \frac{c_o}{c_c} = \overline{K} \frac{x}{\sqrt{a_o}} \,!$$

Experiment:

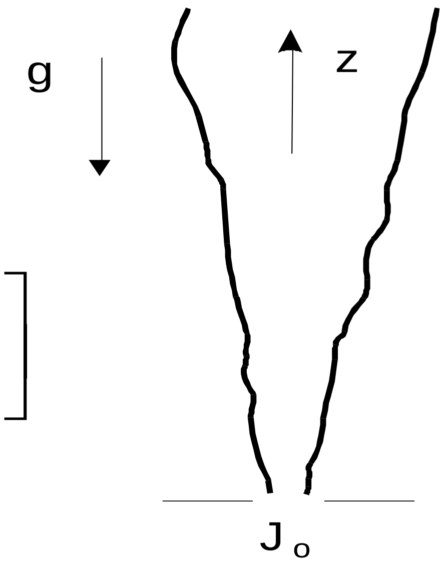
$$\frac{c_c}{c_o} = \frac{7.1}{\frac{x}{D}}, \qquad S_c = 0.14 \frac{x}{D}$$ centerline dilution

Dimensional analysis

- Simple Plume

$(J_o, z) \qquad b \sim z,\ u_c \sim z^{-1/2},\ S_c \sim z^{5/3}$

$$J_o = \left[\frac{L^4}{T^3}\right]$$



Buoyant jets

Dimensional analysis:

Any buoyant jet property e.g. $x = f(z, M_o, J_o, q_o, D\ldots)$

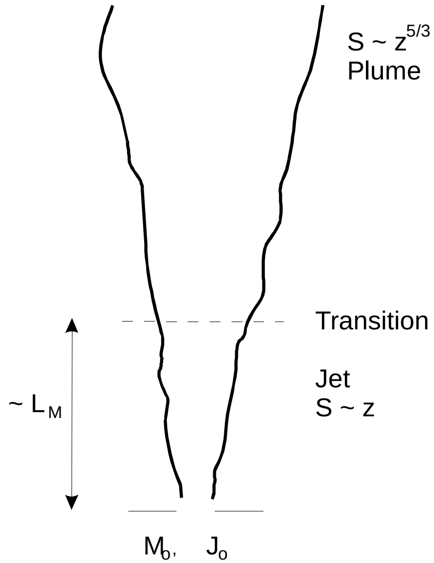
Normalized property $= f\left(\frac{z}{L_M}\right)$

$$L_M = \frac{M_o^{3/4}}{J_o^{1/2}} = \text{momentum length scale}$$

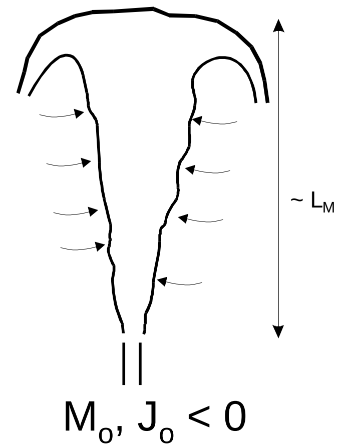
Thus: $DF_o = \left(\frac{4}{\pi}\right)^{1/4} L_M$ correct scaling! $L_M \sim DF_0$

Buoyant jets transitions

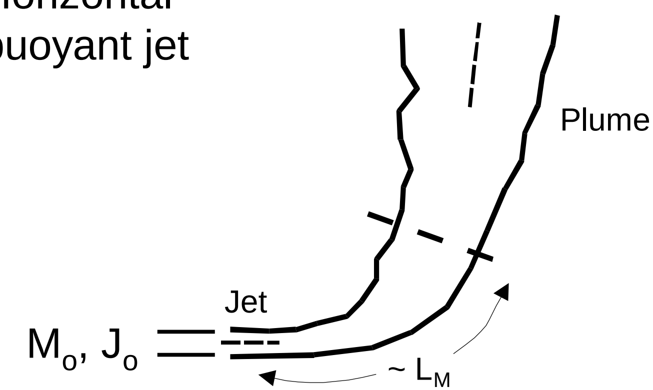
Vertical buoyant jet

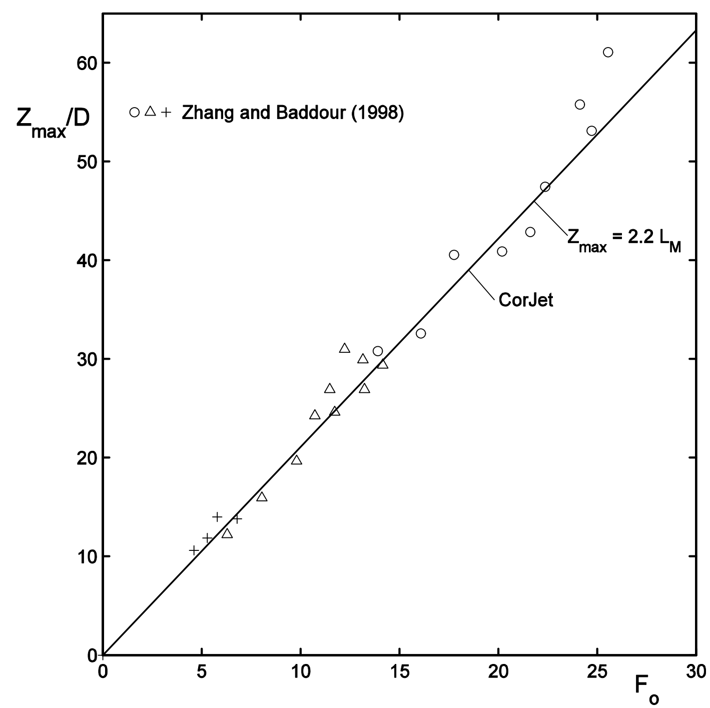


Vertical negatively buoyant jet

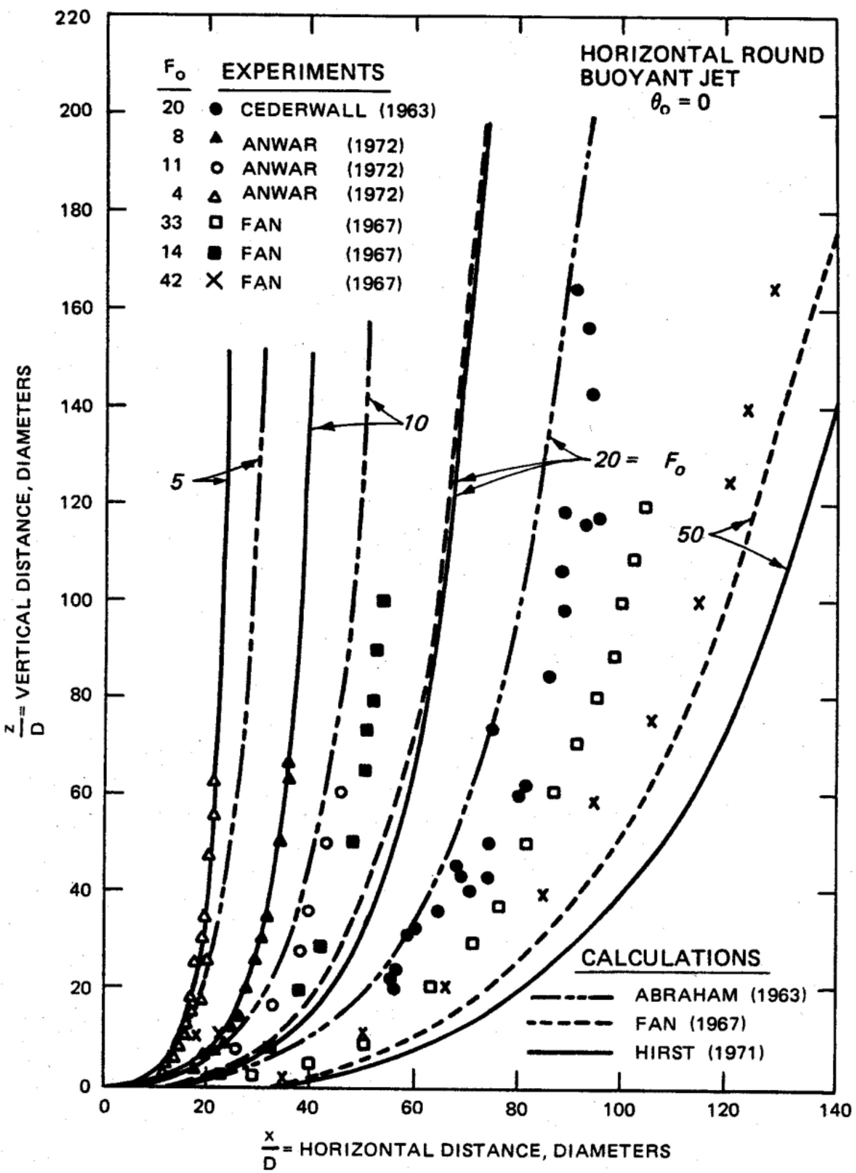


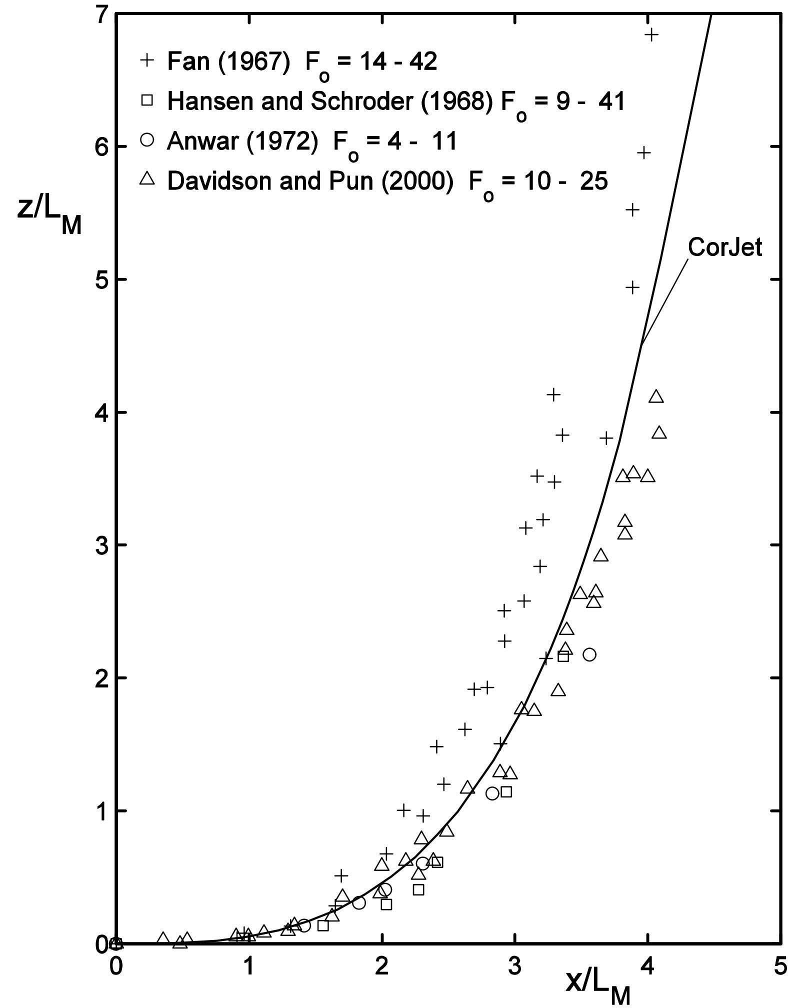
Horizontal buoyant jet





Horizontal buoyant jets





Horizontal buoyant jet in stagnant ambient: Normalized vertical trajectory as a function of L_M

Dilution equations – single port

POSITIVELY BUOYANT !

- Stagnant water, horizontal discharge:

  centerline dilution

$$S_c = 0.54F_o\left(0.38\frac{z}{DF_o} + 0.66\right)^{5/3} \qquad \text{for } \frac{z}{D} \geq 0.5F_o$$

- Ambient stratification:

$$z_{max} = 3.98J_o^{1/4}\varepsilon^{-3/8} \qquad \text{terminal level}$$

$$S_c = 0.071\frac{J_o^{1/3}z_{max}^{5/3}}{Q_o}$$

- Ambient crossflow:

weak deflection $\frac{Hu_a^3}{J_o} < 5$: $S_m = 0.31\frac{J_o^{1/3}H^{5/3}}{Q_o}$ minimum dilution at surface

strong deflection $\frac{Hu_a^3}{J_o} > 5$: $S_m = 0.32\frac{u_aH^2}{Q_o}$

Design example: Sewage discharge

- Water depth H = 15m
- Port diameter D = 0.15m
- Discharge velocity U0 = 1m/s
  - → Flowrate Q0 = U0 D² π/4 = 0.018m³/s
- Δρ/ρ = 0.025 (fresh/salt)
  - → F0 = U0/(Δρ/ρ gD)^(1/2) = 5.2
- → Fluxes:
  - M0 = Q0U0 = 0.018m^4/s²
  - J0 = Q0 Δρ/ρ g = 0.044m^4/s³
- → Length Scales
  - LQ = Q0/M0^(1/2) = 0.13m ~ D
  - LM = M0^(3/4) / J0^(1/2) = 0.74 ~ DF0
- Centerline dilution (stagnant water)

$$S_c = 0.54 F_o \left(0.38 \frac{z}{DF_o} + 0.66 \right)^{5/3} \qquad \text{for } \frac{z}{D} \geq 0.5 F_o$$

- → Sc = 76 (@ z = 0.9H)

Design example: Sewage discharge

- Weak current (ua = 0.05m/s)
  - Lm = M0^(1/2)/ua = 2.68m
  - Lb = J0/ua³ = 35.2m

weak deflection $\frac{Hu_a^3}{J_o} < 5:$ $S_m = 0.31\frac{J_o^{1/3}H^{5/3}}{Q_o}$ minimum dilution at surface

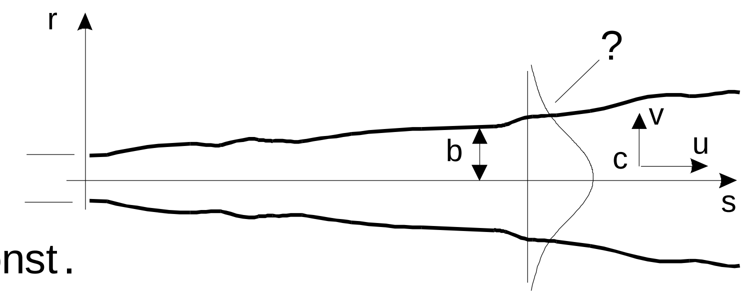
  - Sm = 261

- Strong current (ua = 0.3m/s)
  - Lm = 0.45m
  - Lb = 0.16m

strong deflection $\frac{Hu_a^3}{J_o} > 5:$ $S_m = 0.32\frac{u_a H^2}{Q_o}$

  - Sm = 1220

Formal solution methods



$p_\infty = \text{const.}$

Unknowns (u,v,p,c)

Boundary layer approximations: $\dfrac{b}{s} << 1, \quad \dfrac{\partial}{\partial r} << \dfrac{\partial}{\partial s}$

$$\frac{\partial p}{\partial r} = 0, \quad \frac{\partial p}{\partial s} = 0$$

$$\frac{\partial u}{\partial s} + \frac{1}{r}\frac{\partial rv}{\partial r} = 0$$ Continuity

$$u\frac{\partial u}{\partial s} + v\frac{\partial u}{\partial r} = -\frac{1}{r}\frac{\partial}{\partial r}(r\,\overline{u'v'})$$ Momentum

$$\left[u\frac{\partial c}{\partial s} + v\frac{\partial c}{\partial r} = -\frac{1}{r}\frac{\partial}{\partial r}(r\,\overline{v'c'})\right]$$ Scalar transport (uncoupled)

Jet equation u,v,c

B.C.: $r \to "\infty": \quad \underline{u \to} 0, \ c\ \underline{\to 0},$

$u'v' \to 0, \ v'c' \to 0$

I.C.: $s = 0: \quad u = U_0, \ c = C_0, \ v = 0$

Formal solution methods

Solutions:

- Similarity methods with simple turbulence closure

$$\overline{u'v'} = \varepsilon \frac{\partial u}{\partial r}$$

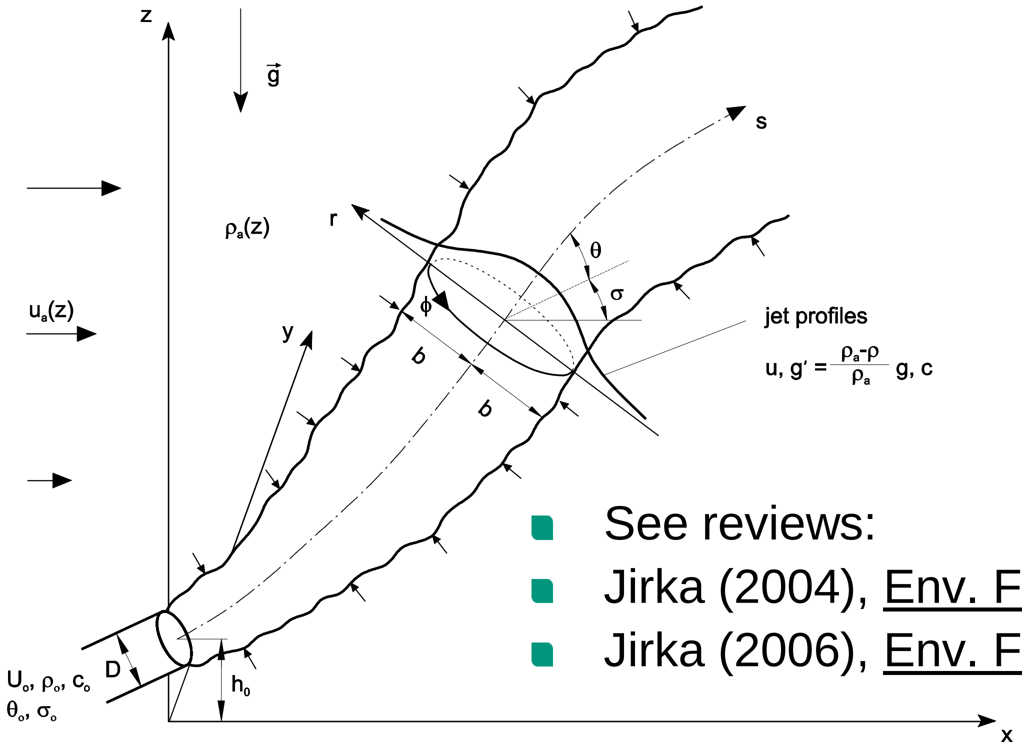
$\Rightarrow$ classical, simple geometries

- Numerical integration (P.D.E.) with advanced turbulence closure e.g. k-ε, LES

  $\Rightarrow$ more general geometries

- Integral methods (conversion to O.D.E.)

CorJet: Buoyant Jet Integral Model



- See reviews:
- Jirka (2004), Env. Fluid Mech., 4,1-56 → single jet
- Jirka (2006), Env. Fluid Mech., 6,43-100 → multiport jets

Definition sketch for three-dimensional buoyant jet discharge into ambient flow with global and local coordinate system, respectively

ambient stratification	ρ_a (z)	non-linear density / temp. / salinity
ambient current	u_a (z)	with skew angle τ_a (z) → Ekman profile
Gaussian profiles	jet width b (e^{-1} – width)	
	dispersion ratio λ	

Integral method for buoyant jet analysis

1. Profile Specification:

$$\frac{u}{u_c} = e^{-r^2/b^2} \qquad b = \text{"}\frac{1}{e} - \text{Width"} \quad (37\%)$$

$$\frac{g'}{g'_c} = \frac{c}{c_c} = e^{-\frac{r^2}{(\lambda b)^2}} \qquad \lambda > 1 \quad \text{"Dispersion ratio" (turbulent Schmidt number)}$$

2. Definition of integral quantities:

Volume flux $$Q = 2\pi\int_o^\infty ur\,dr = 2\pi u_c b^2 \underbrace{\int_o^\infty \left(\frac{r}{b}\right) e^{-\left(\frac{r}{b}\right)^2} d\left(\frac{r}{b}\right)}_{1/2} = \pi u_c b^2$$

Momentum flux $$M = \frac{\pi}{2} u_c^2 b^2$$

Buoyancy flux $$J = \frac{\lambda^2}{1+\lambda^2} \pi u_c g'_c b^2$$

Scalar flux $$Q_c = \frac{\lambda^2}{1+\lambda^2} \pi u_c c_c b^2$$

(„tracer, pollutant“)

CorJet: Buoyant Jet Integral Model

Integral quantities

$$Q = 2\pi \int_0^R u r dr = \pi b^2 \left(u_c + 2u_a \cos\theta \cos\sigma \right)$$ Volume flux (discharge)

$$M = 2\pi \int_0^R u^2 r dr = \frac{1}{2} \pi b^2 \left(u_c + 2u_a \cos\theta \cos\sigma \right)^2$$ Momentum flux

$$J = 2\pi \int_0^R u g' r dr = \pi b^2 \left(u_c \frac{\lambda^2}{1+\lambda^2} + \lambda^2 u_a \cos\theta \cos\sigma \right) g'_c$$ Buoyancy flux

$$Q_c = 2\pi \int_0^R u c r dr = \pi b^2 \left(u_c \frac{\lambda^2}{1+\lambda^2} + \lambda^2 u_a \cos\theta \cos\sigma \right) c_c$$ Tracer mass flux

→Length scales

Jet/plume transition length scale	$L_M = M_o^{3/4} / J_o^{1/2}$
Jet/crossflow length scale	$L_m = M_o^{1/2} / u_a$
Plume/crossflow length scale	$L_b = J_o / u_a^3$
Jet/stratification length scale	$L'_m = M_o^{1/4} / \varepsilon^{1/4}$
Plume/stratification length scale	$L'_b = J_o^{1/4} / \varepsilon^{3/8}$

CorJet: Buoyant Jet Integral Model

- Conservation equations

$$\frac{dQ}{ds} = E$$

$$\frac{d}{ds}\left(M\cos\theta\cos\sigma\right) = Eu_a + F_D\sqrt{1-\cos^2\theta\cos^2\sigma}$$

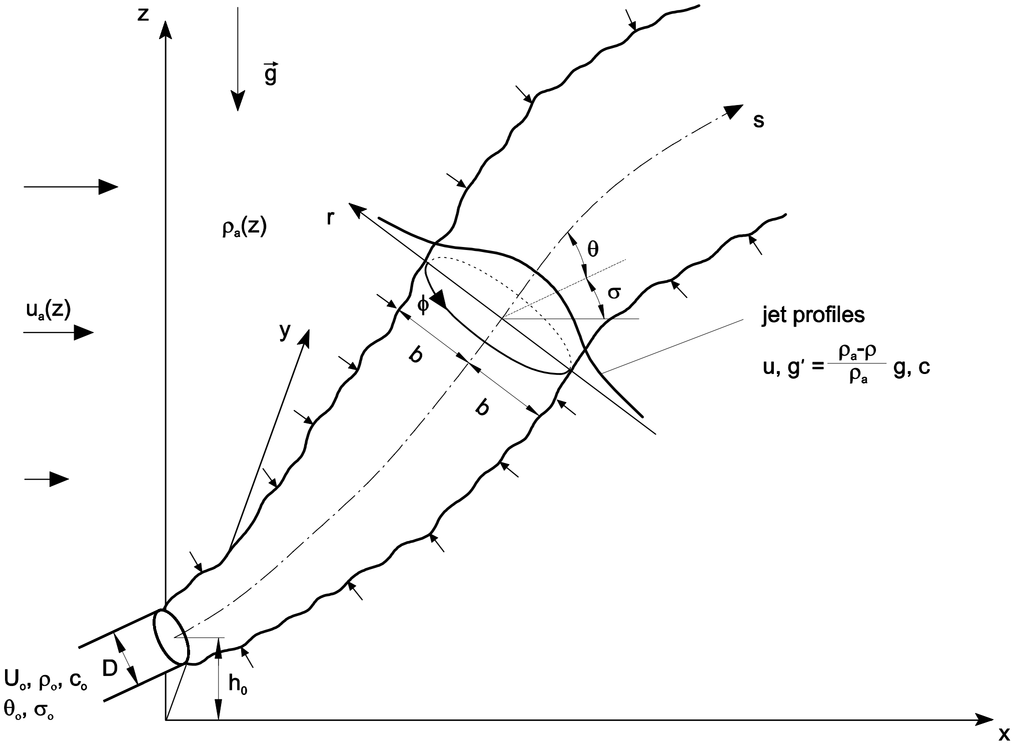
$$\frac{d}{ds}\left(M\cos\theta\sin\sigma\right) = -F_D\frac{\cos^2\theta\sin\sigma\cos\sigma}{\sqrt{1-\cos^2\theta\cos^2\sigma}}$$

$$\frac{d}{ds}\left(M\sin\theta\right) = \pi\lambda^2 b^2 g_c' - F_D\frac{\sin\theta\cos\theta\cos\sigma}{\sqrt{1-\cos^2\theta\cos^2\sigma}}$$

$$\frac{dJ}{ds} = Q\frac{g}{\rho_{ref}}\frac{d\rho_a}{dz}\sin\theta$$

$$\frac{dQ_c}{ds} = 0$$

$$\frac{dx}{ds} = \cos\theta\cos\sigma, \quad \frac{dy}{ds} = \cos\theta\sin\sigma, \quad \frac{dz}{ds} = \sin\theta$$



CorJet: Buoyant Jet Integral Model

Turbulence closure

Entrainment

$$E = 2\pi b u_c \left(\alpha_1 + \alpha_2 \frac{\sin\theta}{F_l^2} + \alpha_3 \frac{u_a \cos\theta \cos\sigma}{u_c + u_a} \right) + 2\pi b u_a \sqrt{1 - \cos^2\theta \cos^2\sigma}\ \alpha_4 \left|\cos\theta \cos\sigma\right|$$

Drag force

$$F_D = c_D 2\sqrt{2} b \frac{u_a^2 (1 - \cos^2\theta \cos^2\sigma)}{2}$$

Universal coefficients:

$$\alpha_1 = 0.055, \quad \alpha_2 = 0.6, \quad \alpha_3 = 0.055, \quad \alpha_4 = 0.5$$
$$\lambda = 1.20, \quad c_D = 1.3$$

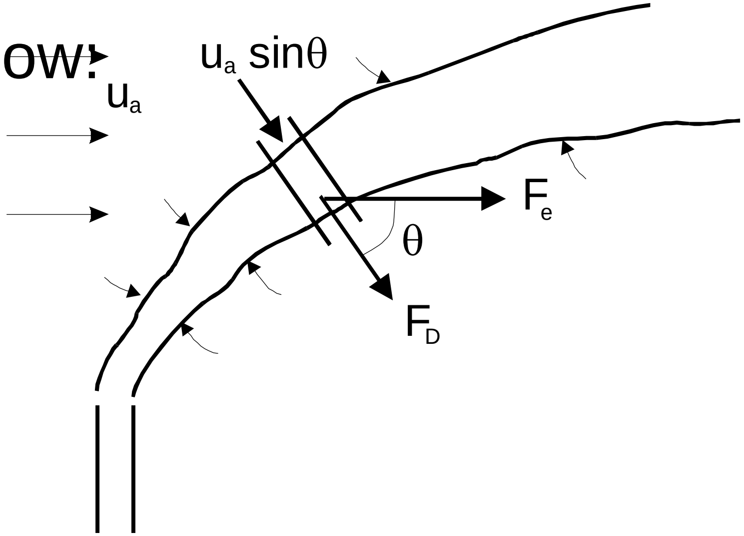
Initial conditions: Zone of Flow Establishment ZOFE

$$L_e = 5.0 D (1 - 3.22 \sin\gamma_o / R)(1 - e^{-2.0 F_o / F_{1p}}) \qquad with \qquad R = \frac{U_o}{u_a}, \quad F_o = \frac{U_o}{\sqrt{g_o' D}}$$

$$Q_e = \sqrt{2}\, Q_o, \quad M_e = M_o, \quad J_e = J_o, \quad Q_{ce} = Q_{co}$$

Amplifications of the integral method

- Crossflow:



Entrainment force =

$$F_e = u_a \frac{dQ}{ds}$$

Drag force =

$$F_D = C_D \frac{(u_a \sin\theta)^2}{2}(2b)$$

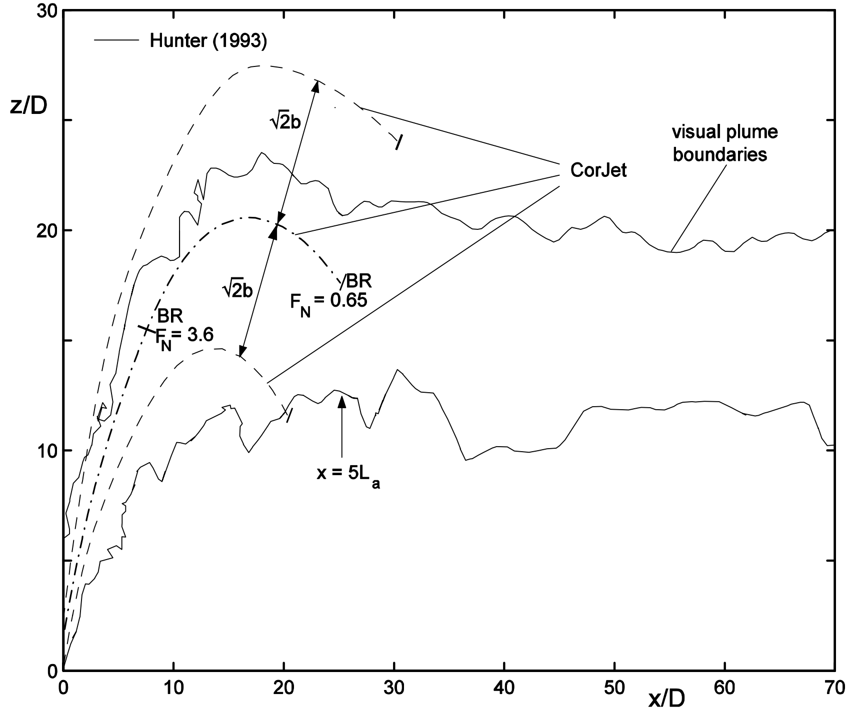
(2) $$\frac{dM}{ds} = \pi\lambda^2 g'_c b \sin\theta + F_e \cos\theta$$

(3) $$\frac{dM\cos\theta}{ds} = F_D \sin\theta + F_e$$

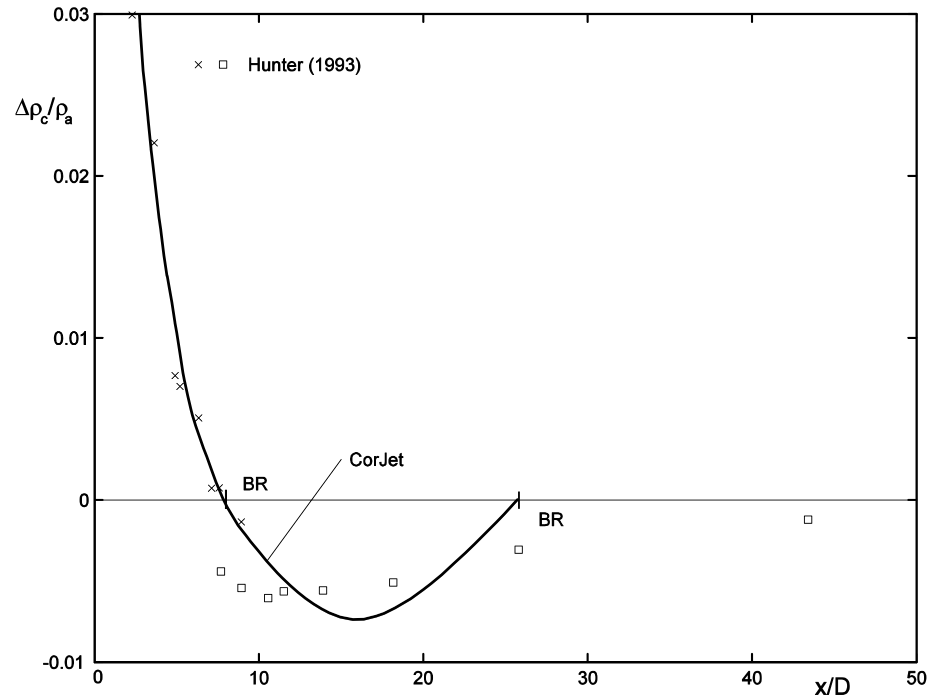
Entrainment $\rightarrow$ additional components: $E = 2\pi b u_c \left(\alpha_1 + \frac{\alpha_2 \sin\theta}{F_\ell^{\,2}} \right) + 2\pi b u_a \alpha_3 \sin\theta \cos\theta$

$R = \frac{u_a}{U_o}$ Crossflow parameter

Buoyant jet in crossflow with stratification



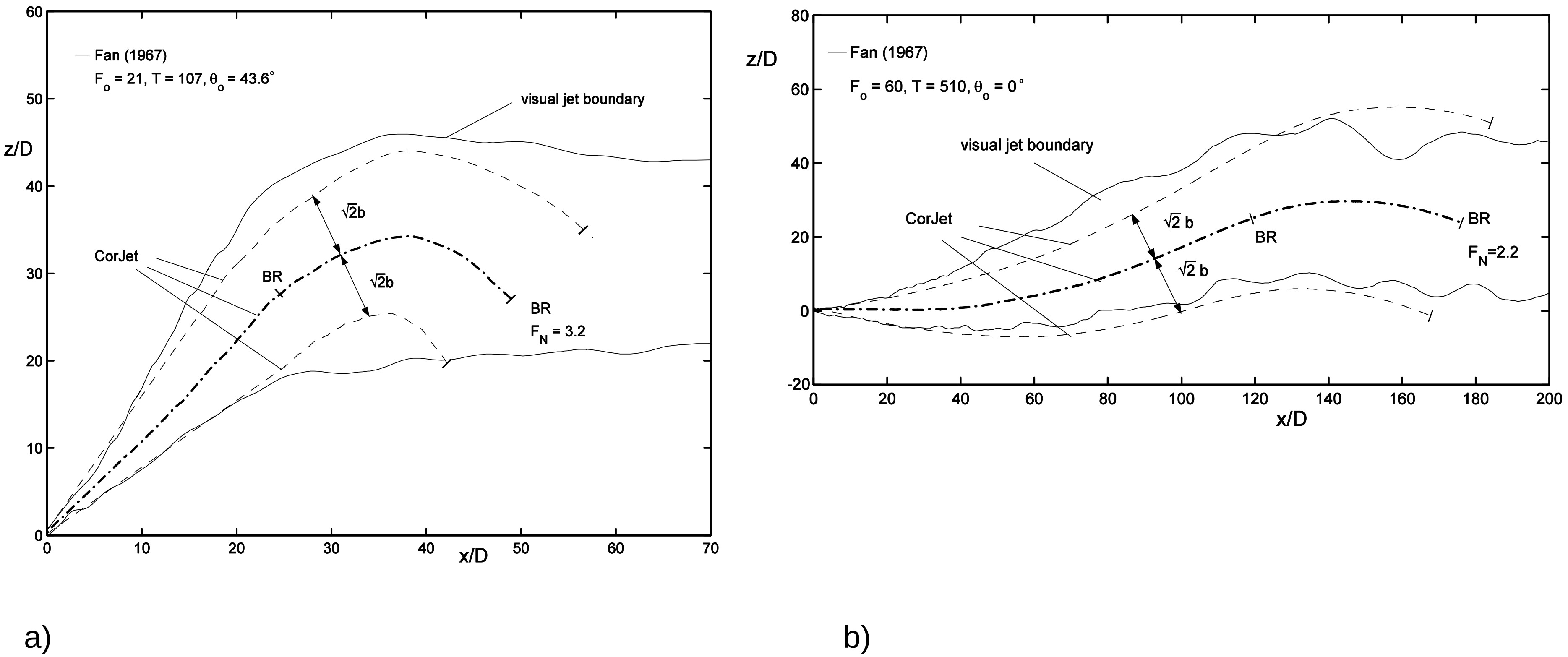
a)



b)

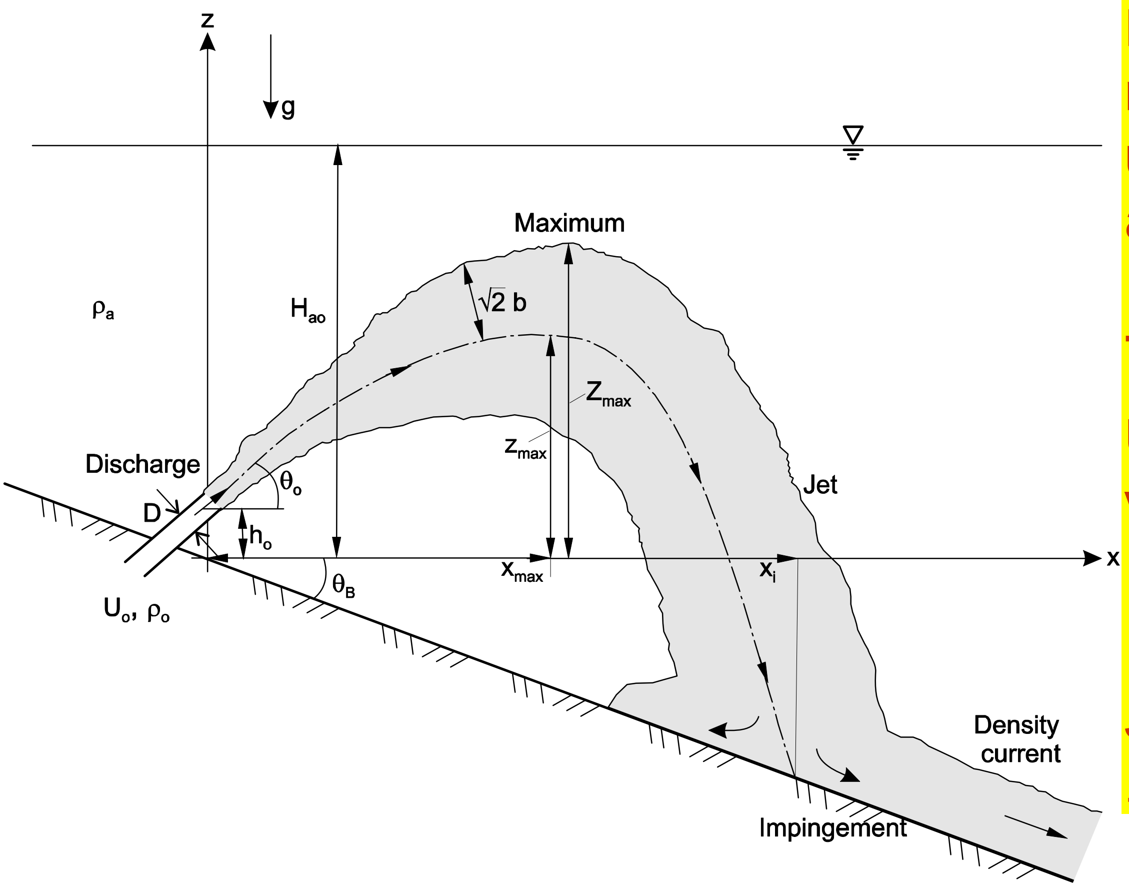
Vertical buoyant jet into stratified crossflow: Comparison of integral model predictions with laboratory data by Hunter (1993) under weak crossflow conditions:
a) vertical trajectory, z/D versus x/D, b) centerline centerline density anomaly $\Delta\rho_c/\rho_a$ as function of downstream distance x/D

CorJet: Buoyant Jet Integral Model



Buoyant jet in stagnant linearly stratified environment: Comparison of integral model predictions with experimental data by Fan (1967) for the two-dimensional trajectory: a) inclined moderately buoyant jet, b) horizontal weakly buoyant jet. For symbols see Fig. 17

Modeling of brine discharges
→engineering design

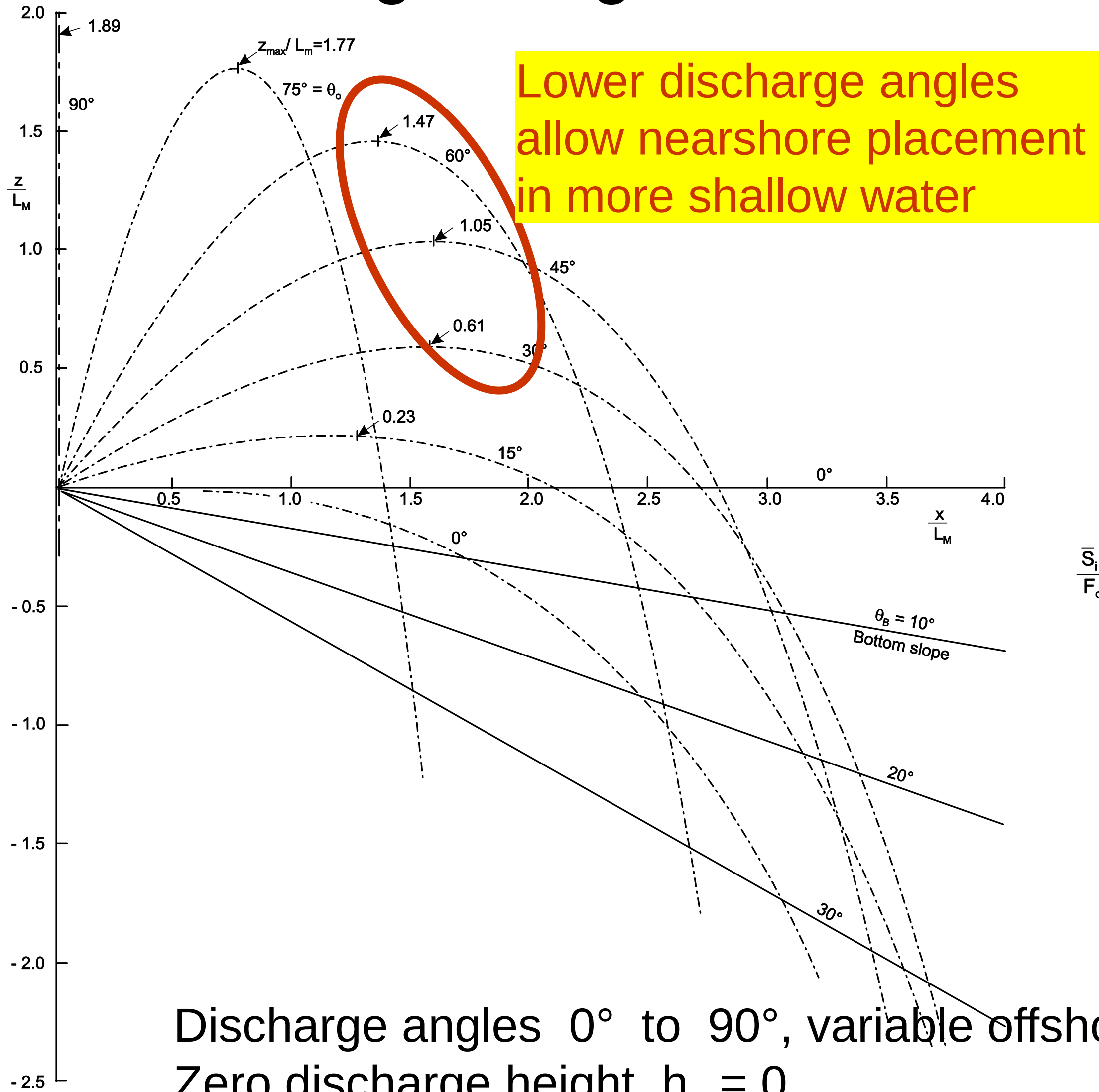


Goal:
Maximize dilution within negatively buoyant jet up to **impingement point** and within **available water depth**

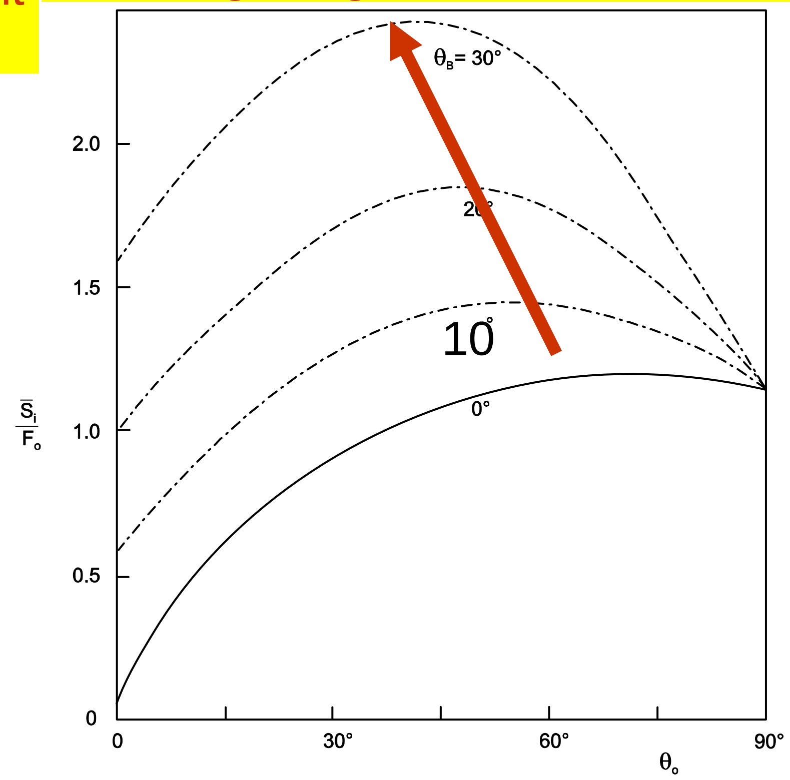
Tool:
Use CorJet as appropriately validated model

Reference:
Jirka (2008), J.Hydr.Eng., 134, 116-120

Brine discharge design

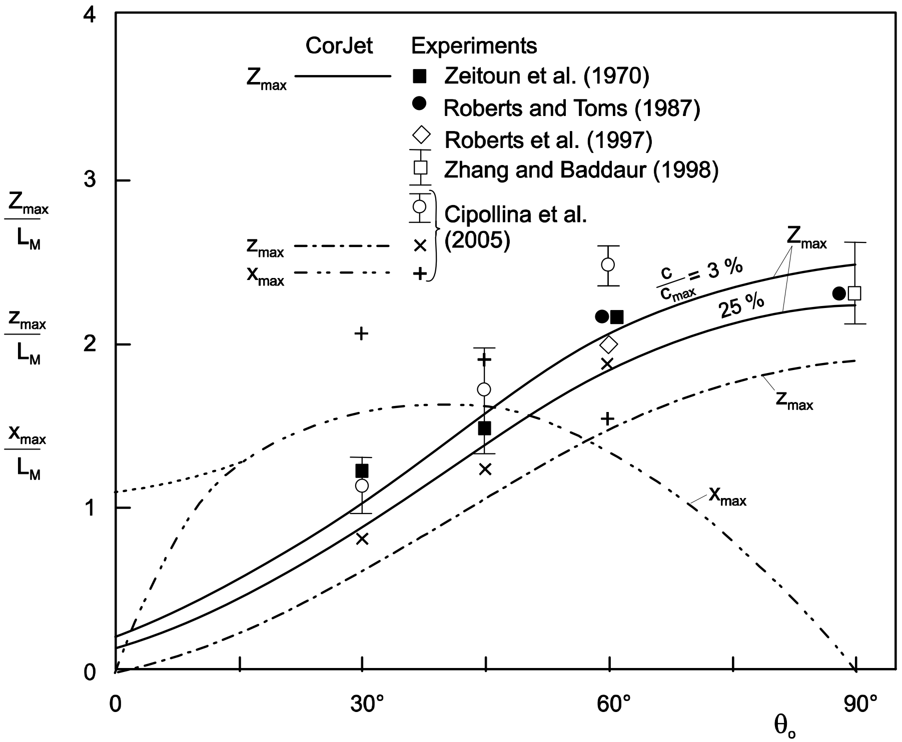


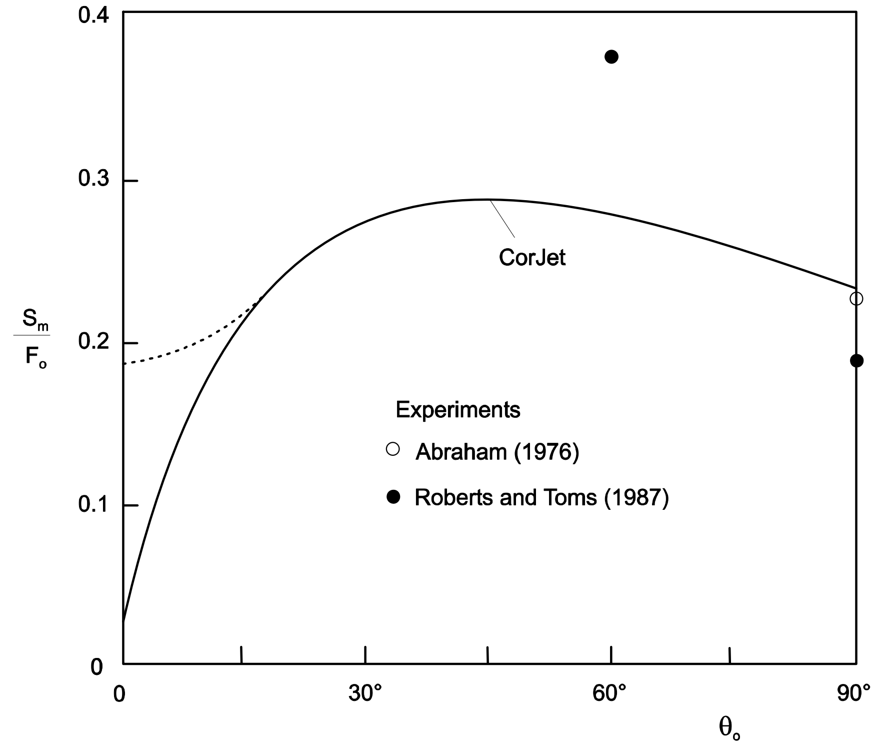
Offshore slopes θ_B and discharge height h_o favor designs with lower discharge angles



Discharge angles 0° to 90°, variable offshore slopes θ_B from 0° to 30°.
Zero discharge height, h_o = 0.
(a) Jet trajectories, (b) Bulk dilutions at impingement, as a function of discharge angle θ_o.

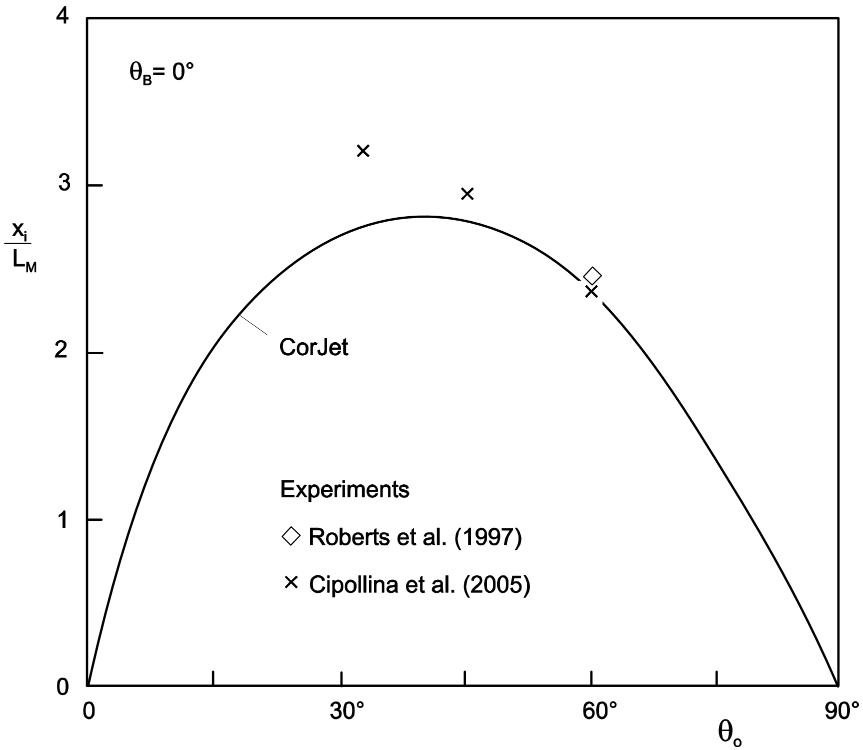
Brine discharge design

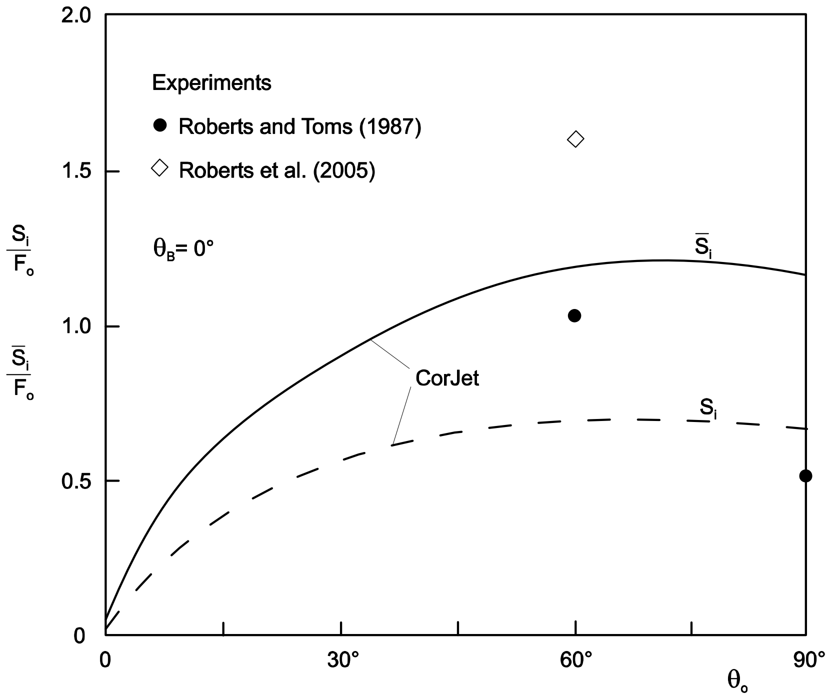




Jet properties at maximum level of rise.
Comparison of CorJet model with experimental data.
(a) Geometric properties,
(b) Minimum centreline dilution, both as a function of discharge angle θ_o.

Brine discharge design



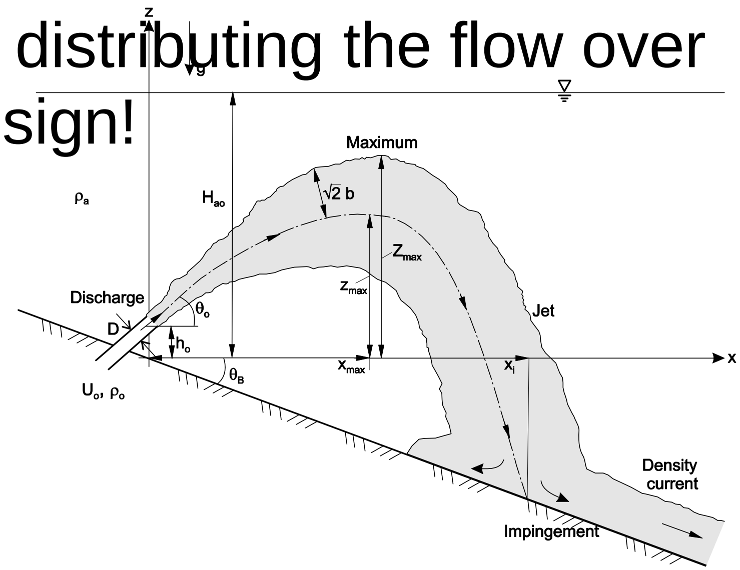


Jet properties at impingement point for zero offshore slope (θ_B = 0°).

(a) Location x_i/L_M, (b) Dilution levels, as a function of discharge angle θ_o.

Brine discharge design: DESIGN RECOMMENDATIONS:

- 1) Choose high discharge Froude number $F_o > 10$, best 20 to 25
- 2) Choose discharge angle 30° to 45°, depending on bottom slope and port height
- 3) Given bottom slope and port height (0.5 to 1 m), choose location at a depth H, so that maximum upper jet boundary Z_{max} is below 0.75 H in oder to avoid dynamic interference with water surface
- 4) Large discharge flow may require distributing the flow over several ports → multiport diffuser design!

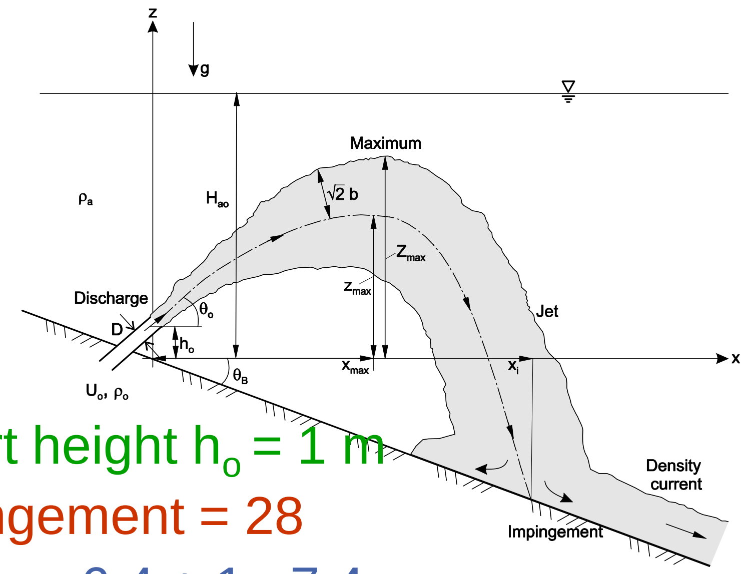


Define and optimize discharge conditions, Jirka (JHydrEng, 2008)

Brine discharge design: DESIGN EXAMPLE:

- Desalination plant serving 100.000 people
- → 200 l/person, day → 20.000 m^3/d, i.e. approx. 0.2 m^3/s
- RO-Plant with 50% recovery rate → discharge $Q_o = 0.2\ m^3/s$
- $g'_o = 0.025*9.81 = 0.25\ m/s^2$ → buoyancy flux $J_o = 0.05\ m^4/s^3$
- Choose: Densimetric Froude number $F_o = 20$

$$D = \left[(4/\pi) Q_o / \left(F_o |g'_o|^{1/2} \right) \right]^{2/5}$$



- → D = 0.23 m
- → $U_o = Q_o/(D^2\pi/4) = 4.84\ m/s$
- → momentum flux $M_o = 0.96\ m^4/s^2$

→ $L_M = M_o^{3/4}/J_o^{1/2} = 4.34\ m$

- Choose: discharge angle $\theta_o = 30°$ and port height $h_o = 1\ m$
- → $Z_{max} = 1.1\ L_M = 4.8\ m$, Dilution at impingement = 28

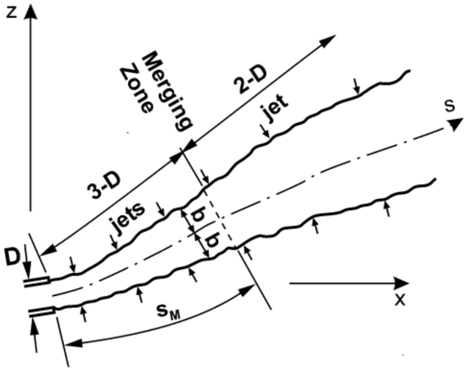
→ Required ambient depth $H = Z_{max}/0.75 + h_o = 6.4 + 1 = 7.4\ m$

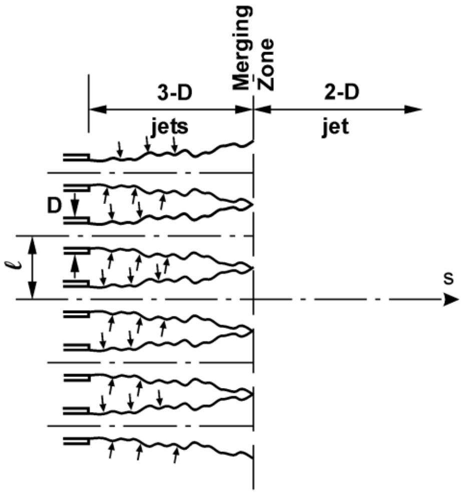
- Compare: would need H = 10.7 m for $\theta_o = 60°$!!!

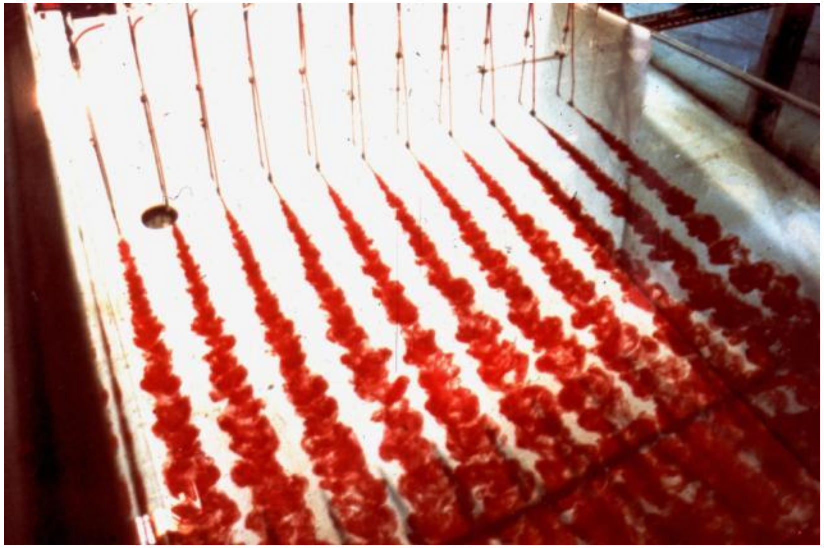
Larger flows may require multiport diffusor!

PLANE BUOYANT JETS

In practice : Multiple jet interaction from mulitport diffuser

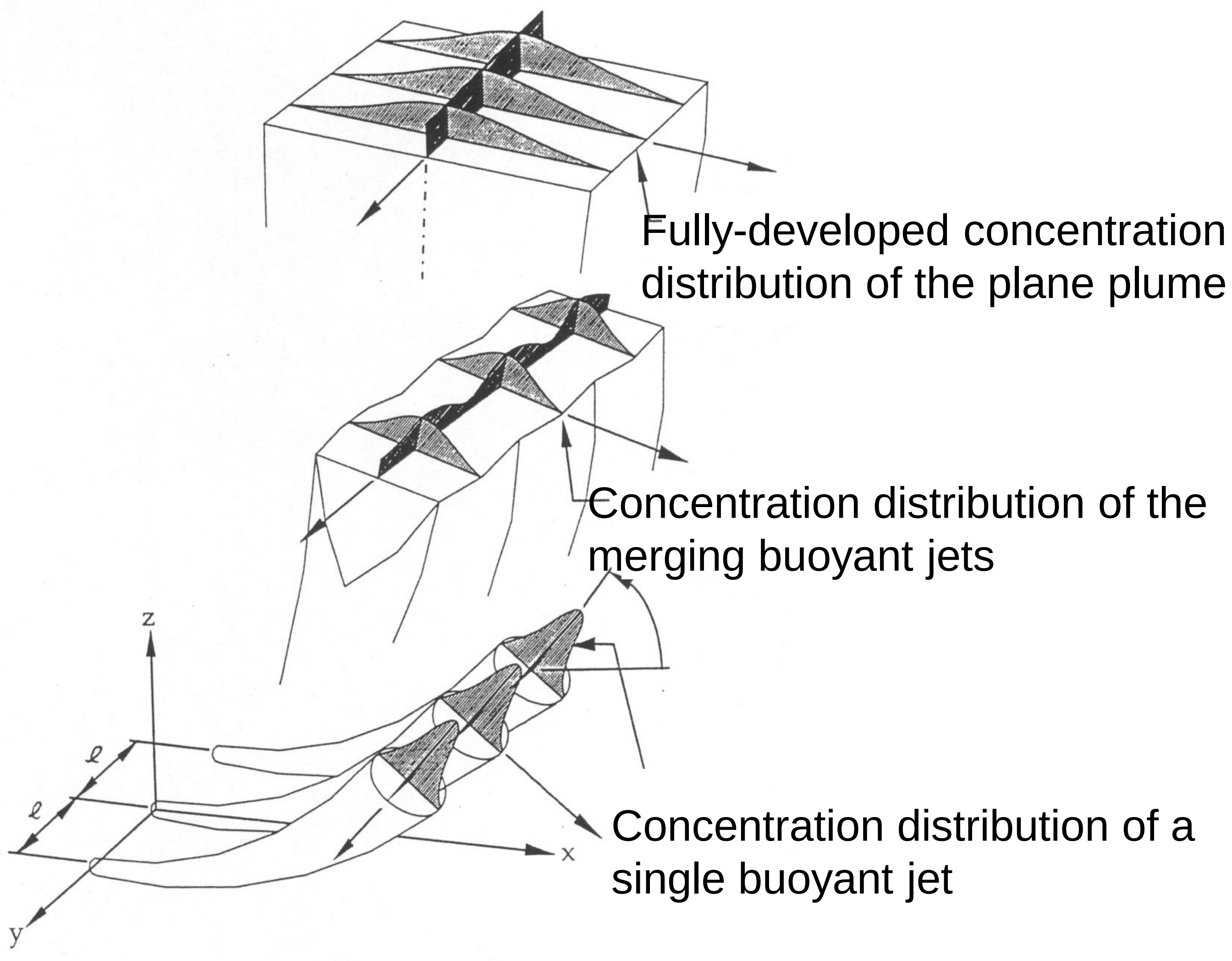






Regular merging processes for a unidirectional diffuser design. (a) Schematic side view and (b) top view under stagnant ambient conditions, (c) photograph of merging under co-flowing ambient conditions (courtesy of I.R. Wood)

Plane Plume concentration distribution formation



PLANE BUOYANT JETS

Idealized: From slot (width B) of finite length L_D

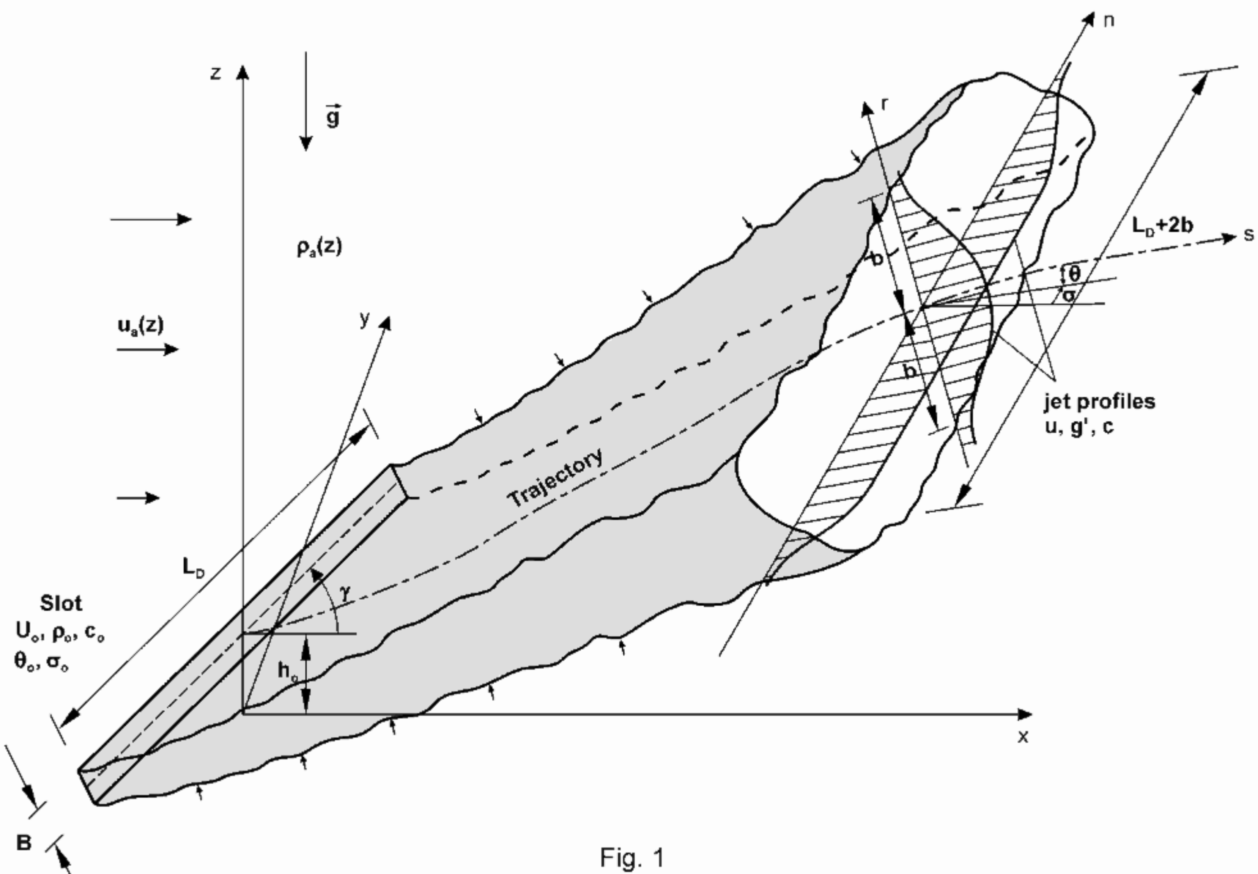


Fig. 1

Definition diagram for plane buoyant jet geometry formed from a finite length slot discharge into unbounded ambient stratified flow with global and local coordinate systems. Slot lies in a horizontal plane at an elevation with alignment relative to *x*-axis

Dilution equations – multiport diffuser line plume

- Stagnant water:

POSITIVELY BUOYANT !

$$S_c = 0.38 \frac{j_o^{1/3} z}{q_o}$$

centerline dilution
Rouse (1952)

- Ambient stratification:

$$z_{max} = 2.84\, j_o^{1/3} \varepsilon^{-1/2} = 2.84 \ell'_b$$

terminal level

$$S_c = 0.31 \frac{j_o^{1/3} z_{max}}{q_o}$$

$$\varepsilon = -\frac{g}{\rho_a} \frac{d\rho_a}{dz}$$

- Ambient crossflow:

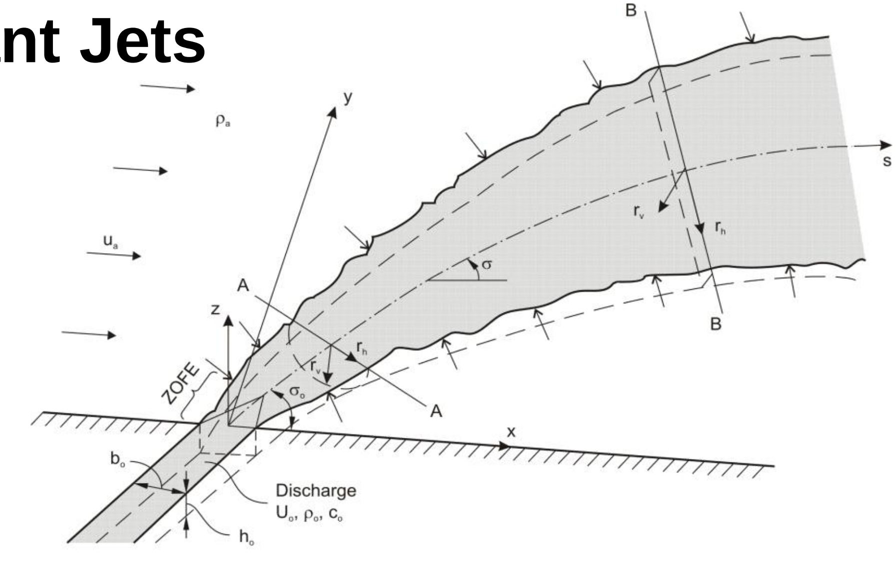
weak deflection $F = \frac{u_a^3}{j_o} < 1$ $S_m = 0.27 \frac{j_o^{1/3} H}{q_o}$ minimum dilution at surface

strong deflection $F > 1$ $S_m = 0.6 \frac{u_a H}{q_o}$ $\gamma = 90°$, perpendicular alignment

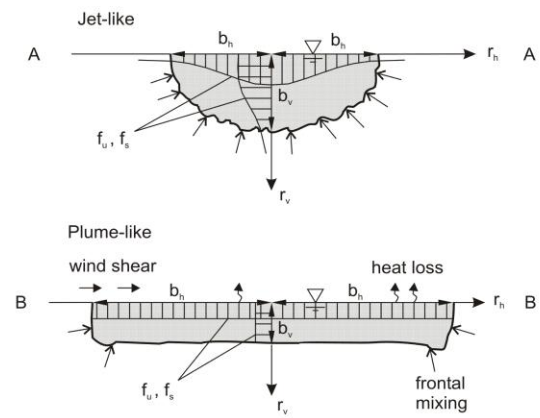
Surface buoyant jet

Source: I. Wood, Univ. of Canterbury

Surface Buoyant Jets



a) Perspective View



b) Cross-Sections

Definition diagram for buoyant surface jet discharging into crossflow without bottom interaction (deep conditions) and a wide channel. (a) Perspective view, and (b) cross-sectional profile, showing the transition from initially jet-like to final plume-like flow conditions. f_u and f_s are the normalized distribution functions for excess velocity and scalars, respectively

CorSurf: Surface Buoyant Jet Integral Model

Reference:

Jirka, G.H., 2005, "Buoyant Surface Discharges into Water Bodies. II: Jet Integral Model", J. Hydraulic Engineering

Deep water conditions

Discharge fluxes of volume Q_o, momentum M_o and buoyancy J_o (in kinematic units)

$$Q_o = U_o a_o,\ M_o = U_o^2 a_o,\ J_o = U_o g'_o a_o$$

Scales: discharge length scale L_Q, jet-to-plume length scale L_M, jet-to-crossflow length scale L_m, and plume-to-crossflow length scale L_b,

$$L_Q = Q_o / M_o^{1/2},\ L_M = M_o^{3/4} / J_o^{1/2},\ L_m = M_o^{1/2} / u_a,\ L_b = J_o / u_a^3$$

Source Froude number Fr_o and crossflow parameter *R*

$$Fr_o = U_o / (g'_o a_o^{1/2})^{1/2},\quad R = U_o / u_a$$

where $Fr_o = L_M / L_Q$ and $R = L_m / L_Q$.

CorSurf: Surface Buoyant Jet Integral Model

Deep water conditions

Integration over normalized distribution functions

$$u = u_c f_u(\eta_h, \eta_v) + u_a \cos\sigma \cos\theta, \quad g' = g'_c f_s(\eta_h, \eta_v), \quad c = c_c f_s(\eta_h, \eta_v)$$

Integral quantities (bulk variables): total volume flux within turbulent zone Q, axial momentum flux M, buoyancy flux J, and tracer mass flux Q_c ,

$$Q = 2b_h b_v \left(a_{Q1} u_c + a_{Q2} u_a \cos\sigma\right)$$

$$M = 2b_h b_v \left(a_{M1} u_c + a_{M2} u_a \cos\sigma\right)^2$$

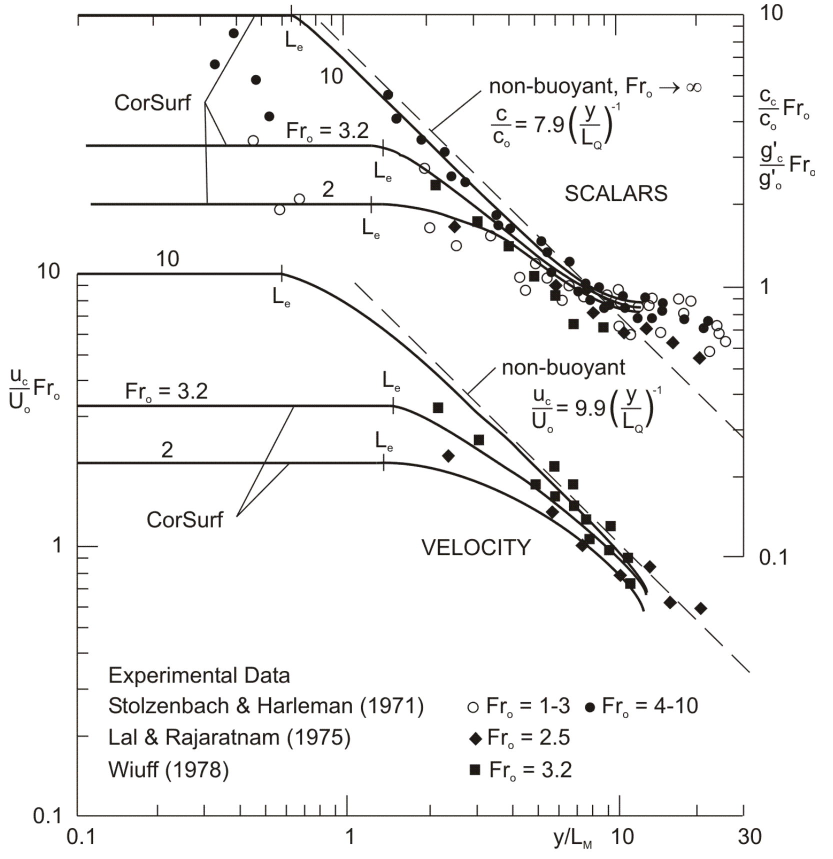
$$J = 2b_h b_v \left(a_{S1} u_c + a_{S2} u_a \cos\sigma\right) g'_c$$

$$Q_c = 2b_h b_v \left(a_{S1} u_c + a_{S2} u_a \cos\sigma\right) c_c$$

CorSurf: Surface Buoyant Jet Integral Model

Model Validation II: Non-Equilibrium Cases

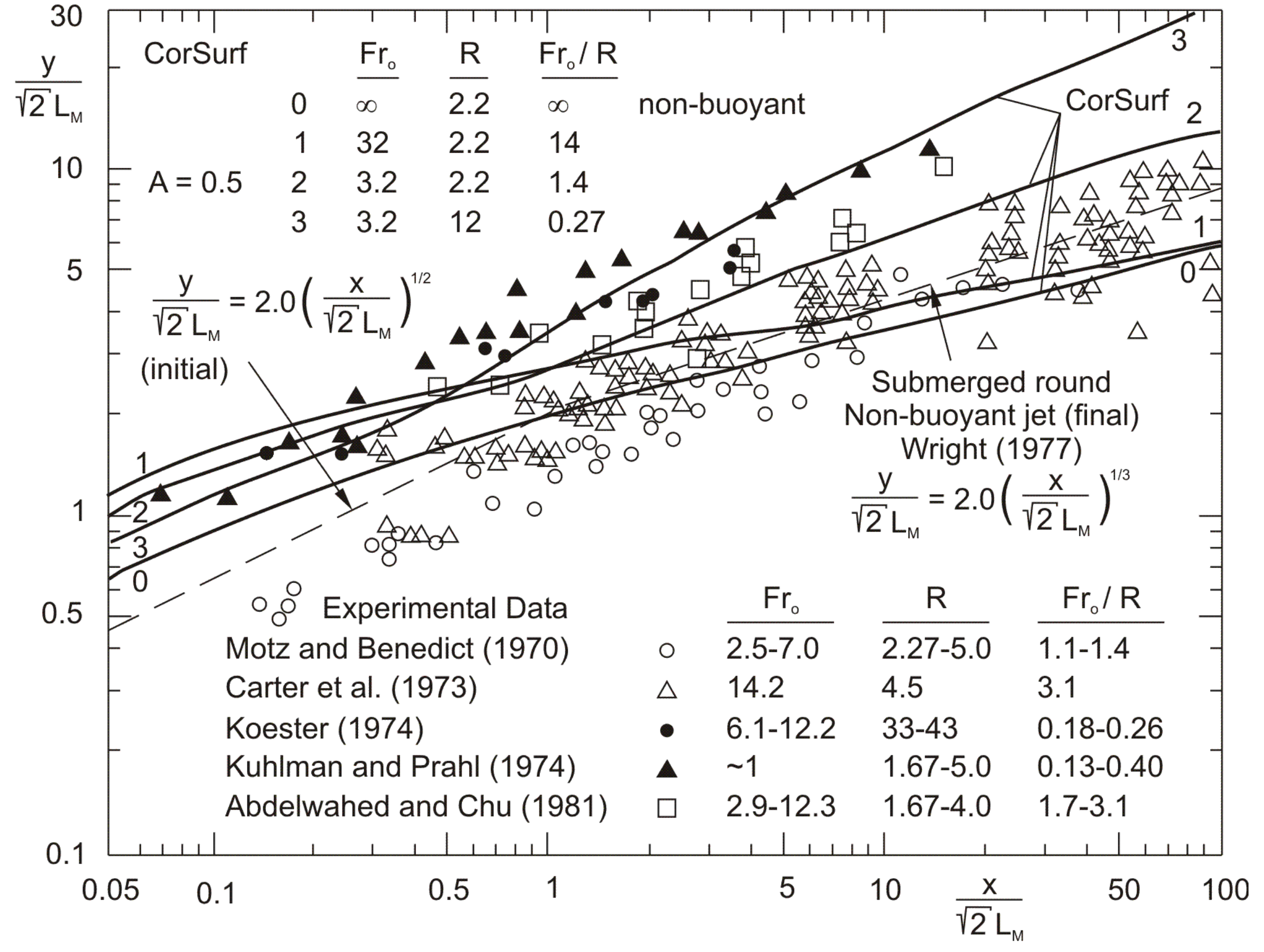
Stagnant Ambient: “Jet Collapse”



Surface buoyant jet in stagnant ambient. Comparison of laboratory experimental data with predictions of integral model CorSurf (with aspect ratio *A* = 0.5). Normalized centerline velocity $(u_c/U_o)Fr_o$, and centerline concentration $(c_c/c_o)Fr_o$, or centerline buoyancy $(g'_c/g'_o)Fr_o$ as a function of offshore distance y/L_M

CorSurf: Surface Buoyant Jet Integral Model

Ambient crossflow:



Free surface buoyant jets in ambient crossflow (flow class FJ1 and Fj2). Comparison of laboratory data with predictions of integral model CorSurf (with aspect ratio *A* = 0.5). Normalized jet centerline trajectories $y/(\sqrt{2}L_m)$ as a function of longshore distance $x/(\sqrt{2}L_m)$. Data and model predictions show dependence on ratio $Fr_o / R = L_M / L_m$

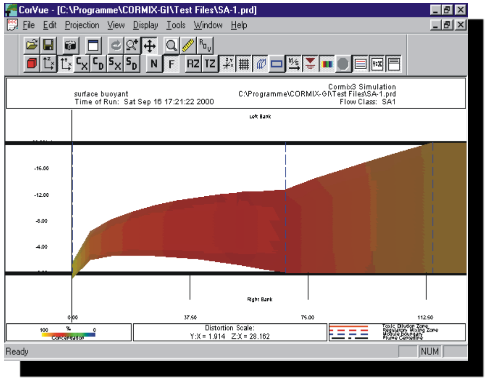
Referencias

IAHR / IWA Committee on Marine Outfall Systems:

www.outfalls.bleninger.info

Modelos:

- CORMIX, www.cormix.info
- Delft3D, www.deltares.nl



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