Maximizing Effluent Dispersion and Minimizing Mixing Zones

Water Environment Federation
People to People
Beijing, China

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Presented by
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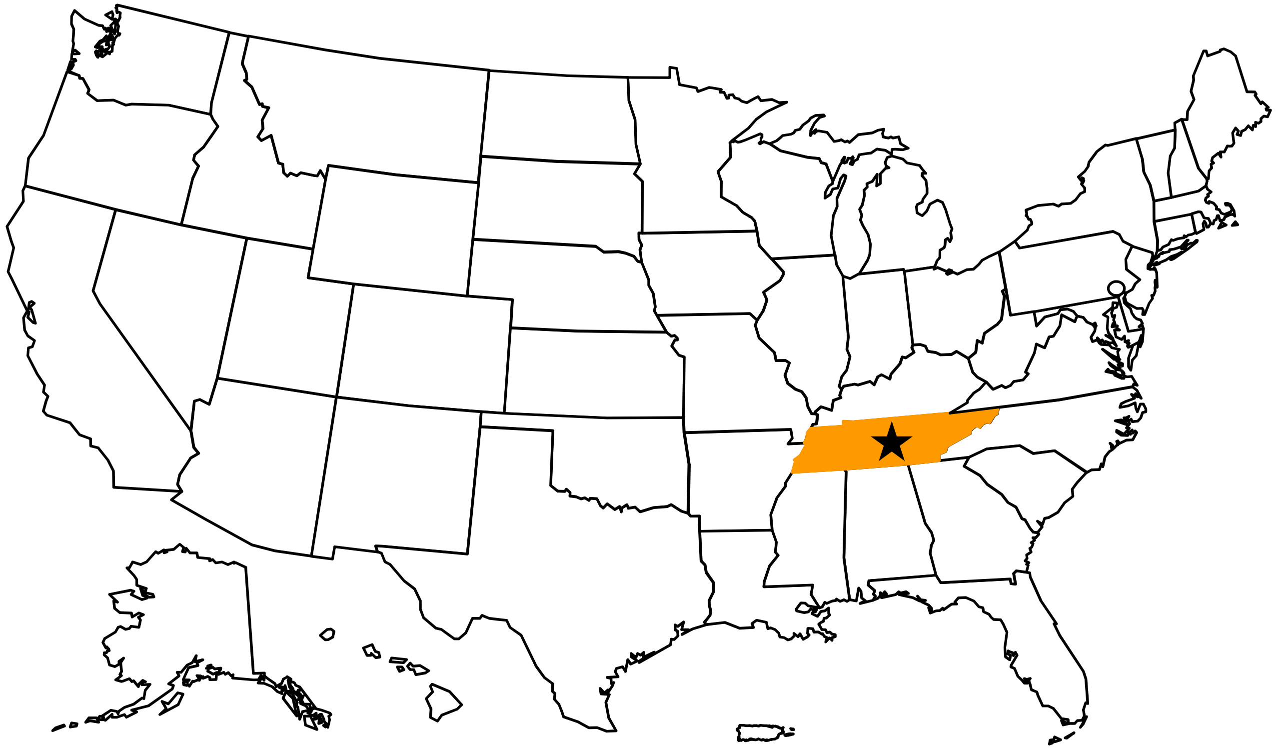
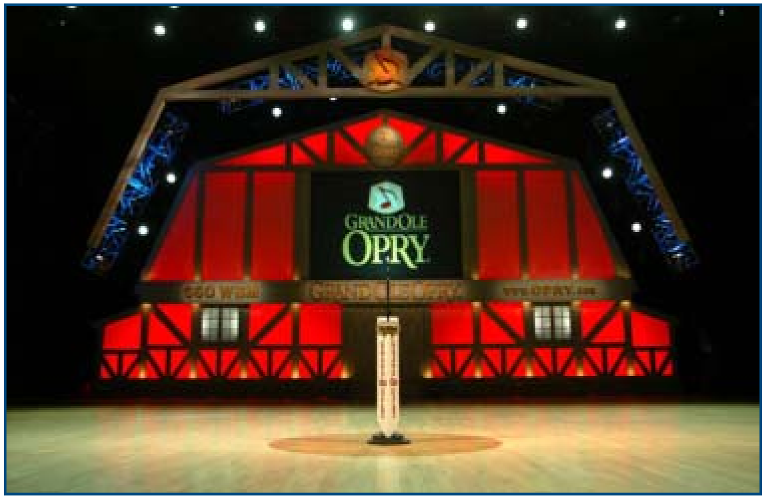
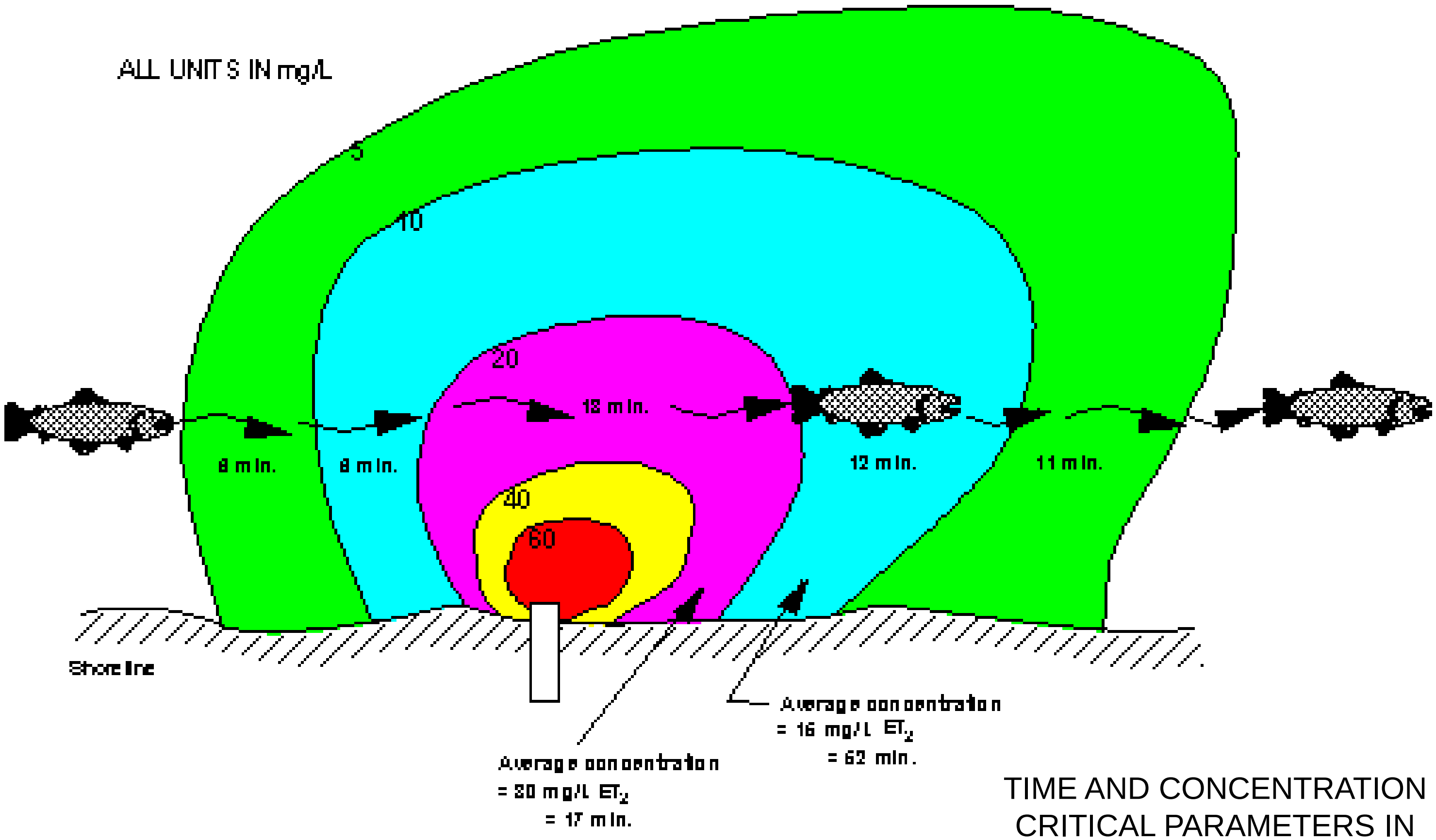




Grand Ole Opry
Home of Country Music

Why Do We Need Mixing Zones?



TIME AND CONCENTRATION CRITICAL PARAMETERS IN EXPOSURE SCENARIO

NATIONAL ACADEMY OF SCIENCES, WATER QUALITY COMMITTEE, 1972

HYPOTHETICAL EXPOSURE SCENARIO FOR FISH PASSING THROUGH A ZID

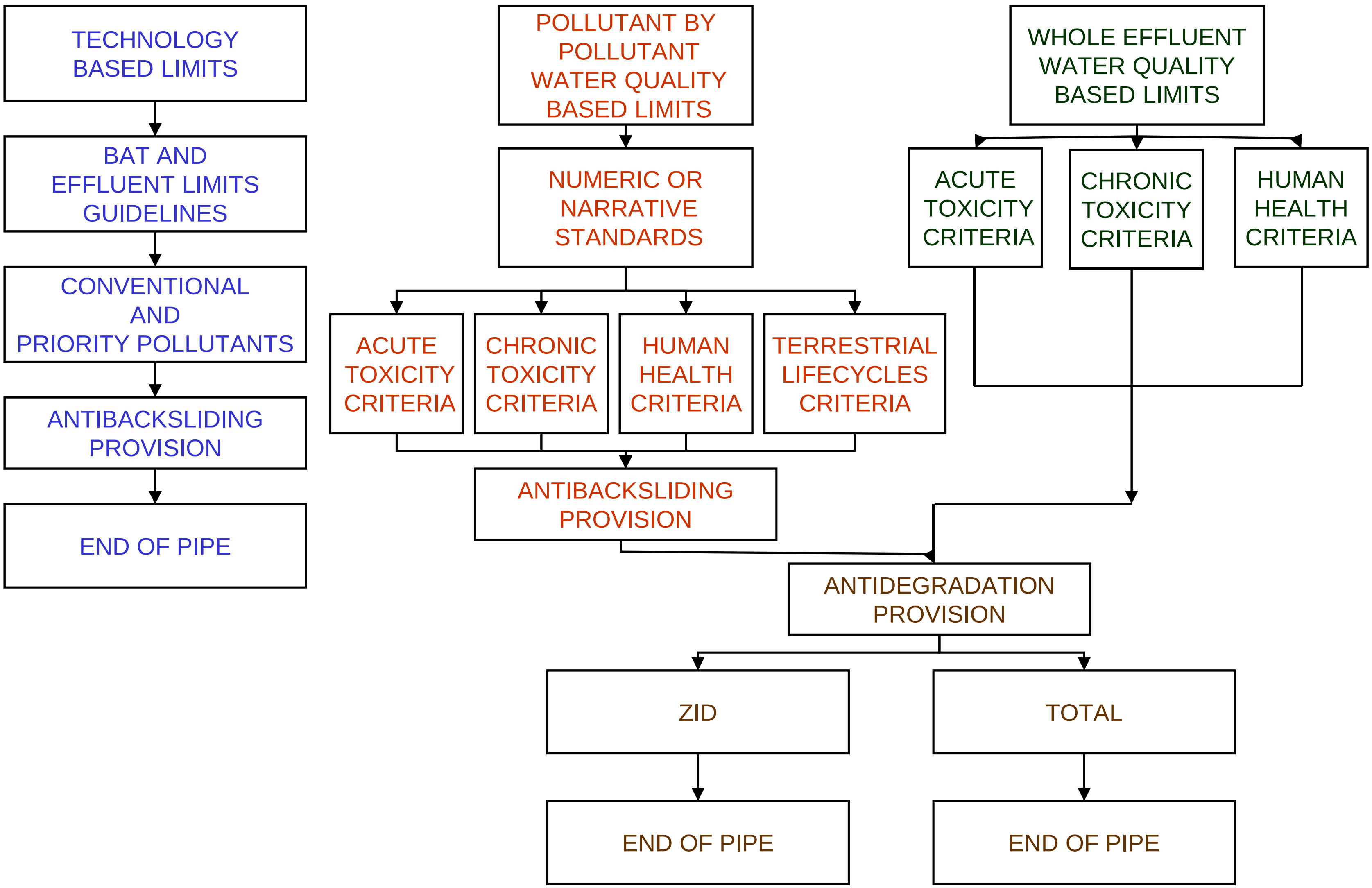


FIGURE 2
CLEAN WATER ACT OF 1987
WATER QUALITY-BASED TOXICS CONTROL

3. Purpose of Mixing Zones

- Achieve Maximum Dispersion in Smallest Area
- Minimize Effects on Receiving Water
- Minimize Acute and Chronic Toxicity in Receiving Stream
- Meet Narrative Water Quality Standards
- Provide Maximum Protection for Receiving Stream
- Maintain Zone of Passage for Fish
- Meet Local or National Mixing Zone Requirements
- Meet Technical Guidance

Oregon Guidelines for Mixing Zones

- Shall be free of concentrations that cause acute toxicity. The Department may on a case by case basis establish a zone of immediate dilution if appropriate for other parameters (including acute and chronic toxicity)
- Shall be free of Nuisance materials
- Limits shall be described in the wastewater discharge permit.
- Avoid overlap with other mixing zones
- Not threaten public health
- Minimize adverse effects on other designated beneficial uses outside the mixing zone

*From “Water Pollution; Division 41; ‘Statewide Water Quality Management Plan; Beneficial Uses, Policies, Standards and Treatment Criteria for Oregon”

Purpose of Diffusers

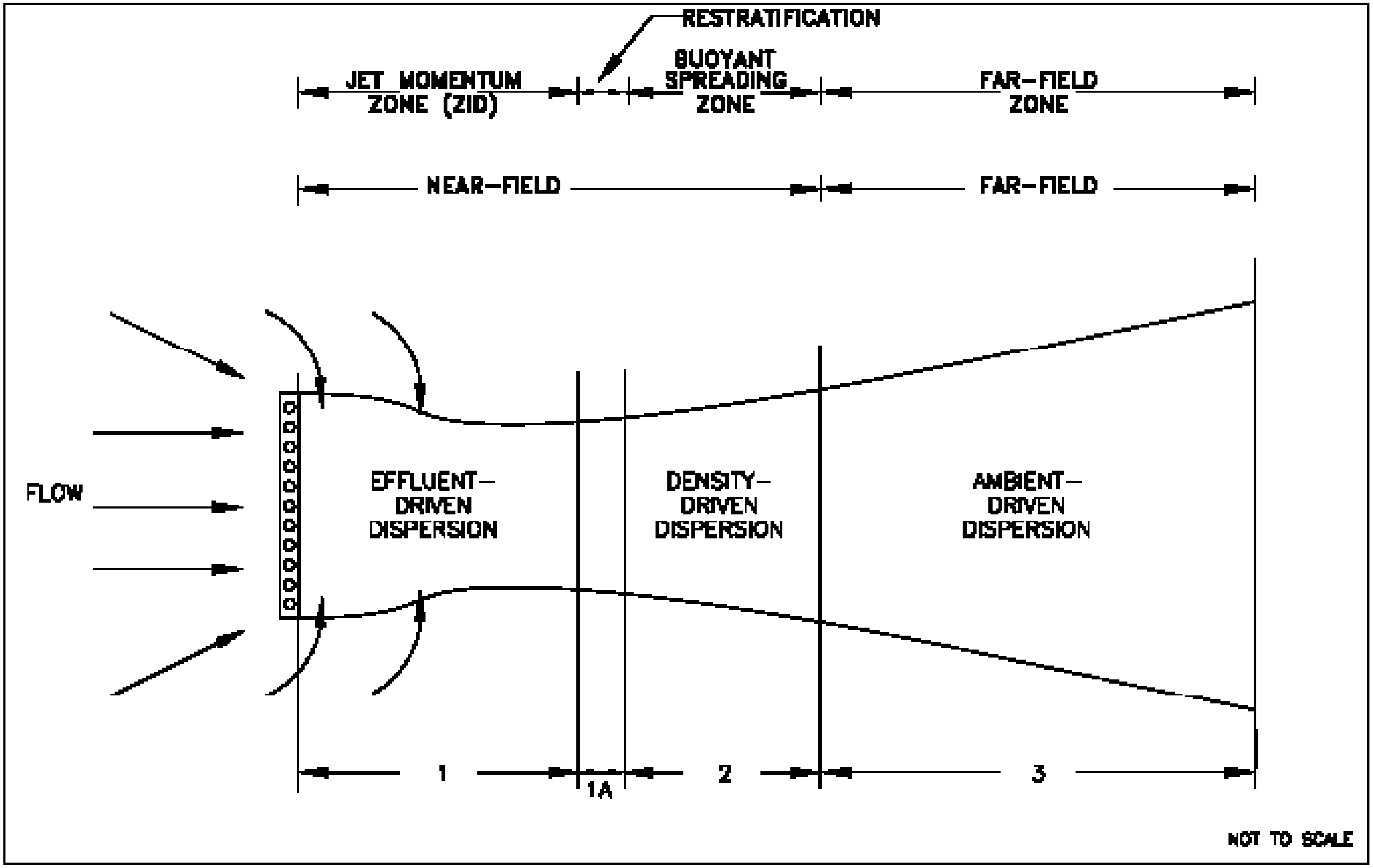
- Provide rapid and immediate dispersion of effluents to prevent adverse effects to the receiving stream

Diffusers

Purpose & Design Considerations

NEED RULES OF THUMB

5. Hydraulic Mixing Zone Concepts



- To Define the Dispersion from Effluent Momentum and Ambient Diffusion

Diffuser Design Considerations

- Effluent Mixing Zone
  - Zone of Initial Dilution (ZID)
  - Total Mixing Zone
- Enhancement of Mixing
  - Side Channel Discharge
  - Single-port or Multi-port Diffuser
  - Real-time Effluent Discharge (tidal or dynamic flows)
- Effluent River Influences on Mixing
  - River Hydraulics and Bathymetry
  - Effluent Flow and Discharge Velocity
  - Density Gradients
  - Flow Changes
  - Contaminant Build-up

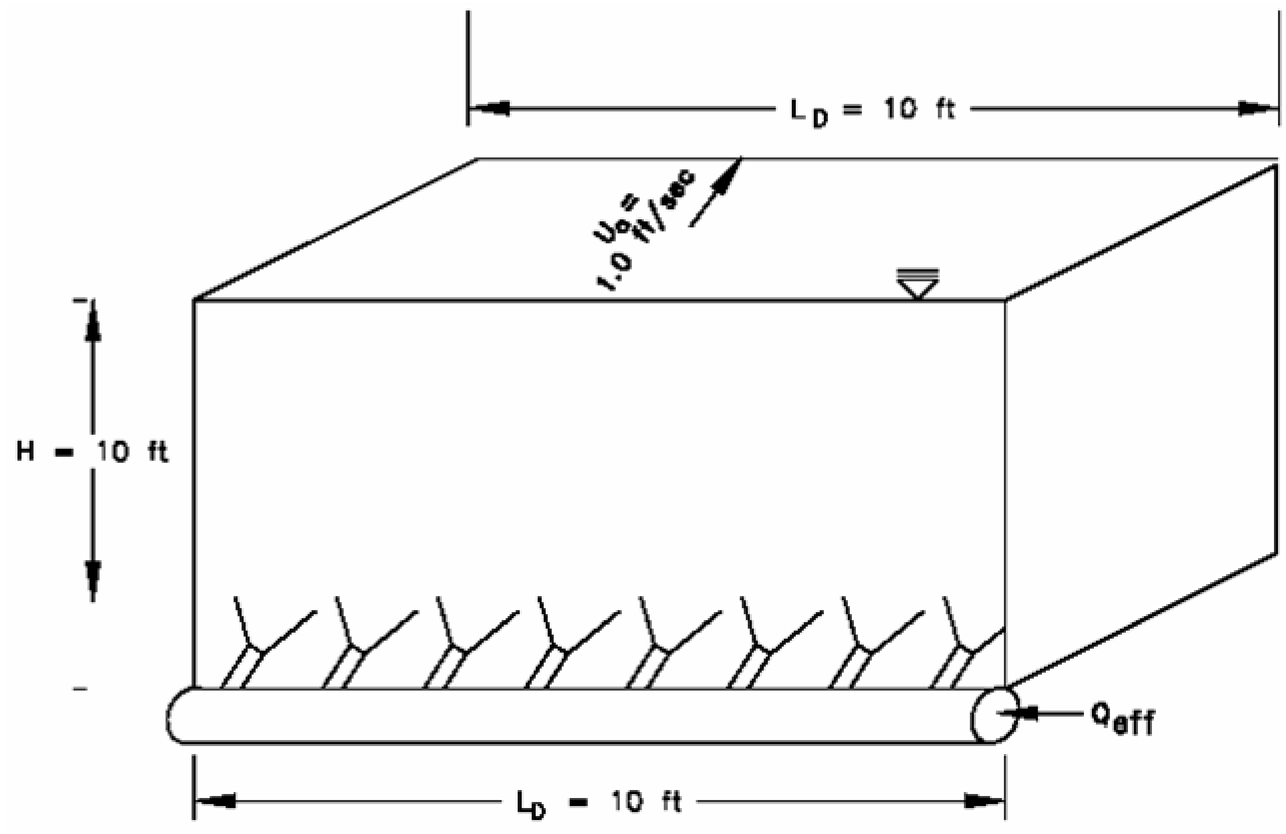
Zone of Initial Dilution (ZID) Cont'd

- Use EPA TSD Guidance
  - Use a high velocity diffuser >/= 10ft/sec to limit exposure to only a few minutes
  - Criterion Maximum Concentration (CMC) standards met:
    - 10% of distance from edge of outfall to edge of mixing zone in any spatial direction
    - Within 50 times the square root of the cross-sectional area of a single port in any spatial direction
    - Within distance of 5 times the local water depth in any spatial direction
    - Spatial is defined in the TSD as a discharge length scale or in the direction of flow. This is also mathematically defined along the centerline of the plume
- Hydraulically on the Order of 1 Diffuser Length (i.e., +/- 0.5 to 1.5 diffuser lengths, but dependent on ambient velocity). Cormix calculates the jet momentum zone to end at the 0.5 diffuser length

Total Mixing Zone (Chronic)

- TMZ is Far-field or Ambient Diffusion
- Far-field technically extends until effluent totally mixed with receiving stream – this may take 13 to 16 km or more
- No Chronic toxicity must be met at edge of this zone
- Zone of free passage limits TMZ in U.S. to 25% of cross-sectional area or volume of flow.

Bulk Dispersion Analysis

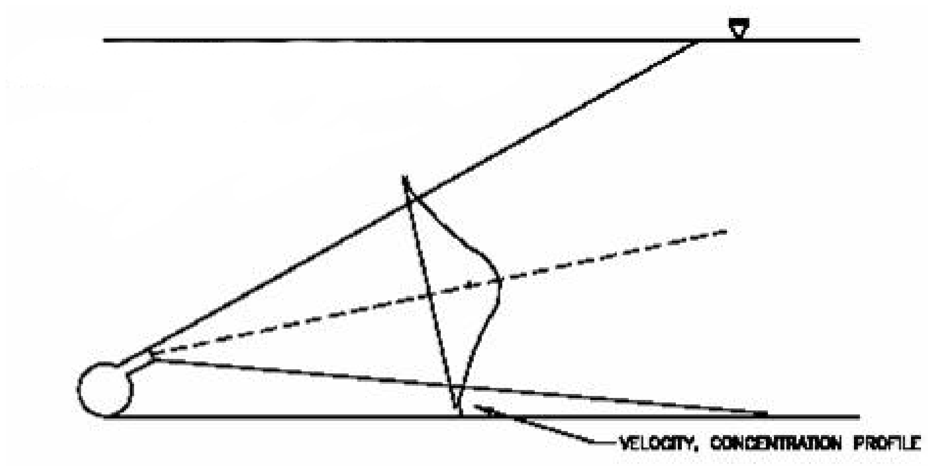


$$\text{ESTIMATE OF DISPERSION} = \frac{(U_0 * H * L_D) + Q_{eff}}{Q_{eff}} = \frac{(1.0\ \text{ft/sec} * 10\ \text{ft} * 10\ \text{ft}) + 5\ \text{cfs}}{5\ \text{cfs}} = \frac{105\ \text{cfs}}{5\ \text{cfs}} = 21:1$$

NOT TO SCALE

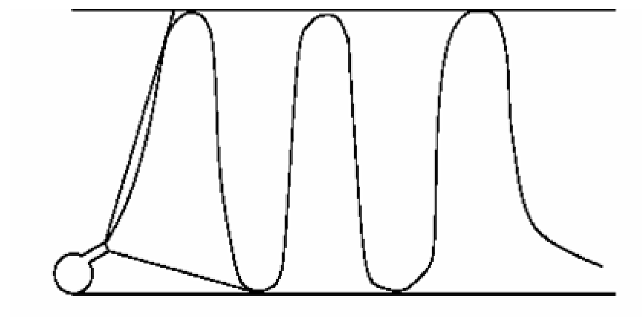
Plume Stability Analysis

STABLE (GAUSSIAN) PLUME



VELOCITY CONCENTRATION PROFILE

UNSTABLE PLUME



$$\frac{m_o}{p_o^{2/3}H} + \frac{m_a + m_o \cos\theta_o}{p_o^{2/3}H} \begin{array}{l} \geq 0.54 \; \textit{unstable} \\ < 0.54 \; \textit{stable} \end{array}$$

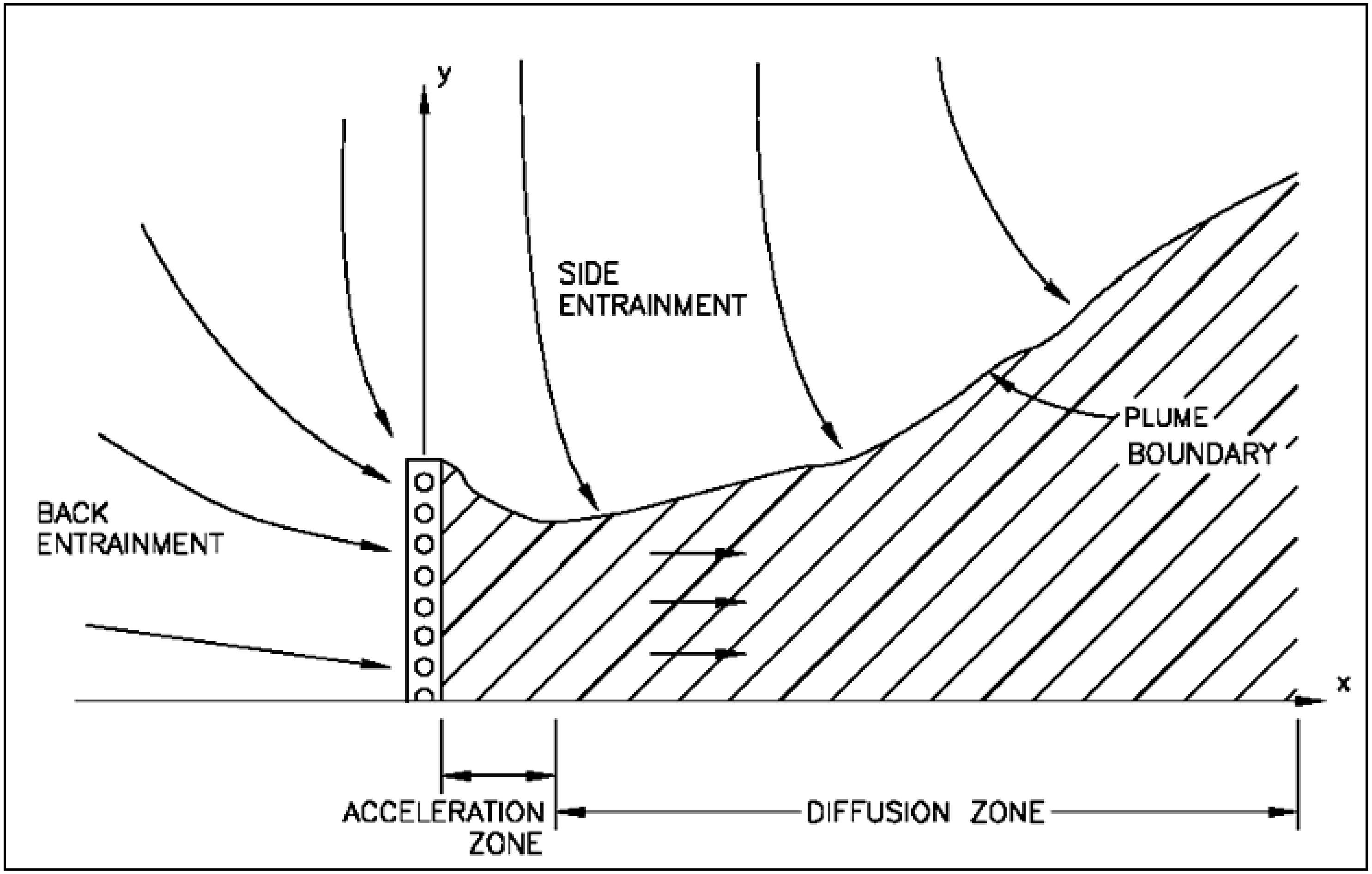
Jirka (1982)

where:	mo	= discharge momentum flux
	ma	= ambient momentum flux
	po	= buoyancy flux
	H	= water depth
	qo	= discharge angle

$$\frac{m_o\left(1 + m_o \cos^2\theta_o\right)^2 + m_a}{p_o^{2/3}H} \begin{array}{l} \geq 0.54 \; \textit{unstable} \\ < 0.54 \; \textit{stable} \end{array}$$

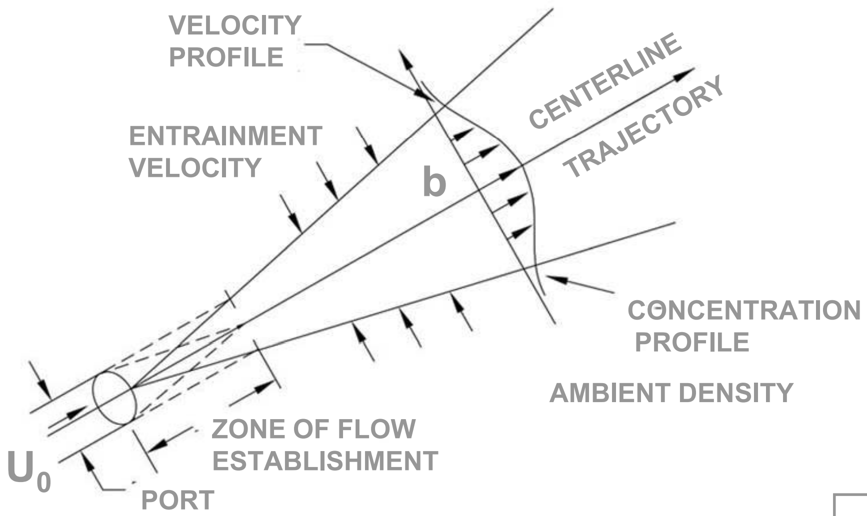
Adams (1982), Jirka (1973,1982)

Jet Zone
Entrainment of Water (1/2 Plume)

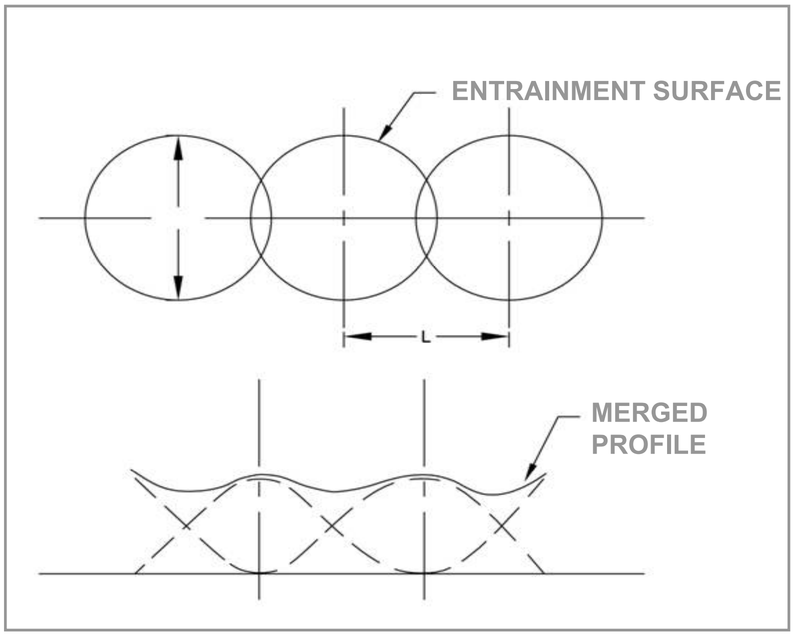


Stable Plume Analysis

(Plan View)



(Profile View)



UDKHDEN Dispersion Model Cont'd

- Zone of Flow Establishment
  - Conservation of Mass: $\frac{d}{ds}\int_0^\infty Vrdr = E$
  - Conservation of Energy: $\frac{d}{ds}\int_0^\infty V(T-T_\infty)rdr = -\frac{dT_\infty}{ds}\int_0^\infty Vrdr$
  - Conservation of Pollutant: $\frac{d}{ds}\int_0^\infty V(C-C_\infty)rdr = -\frac{dC_\infty}{ds}\int_0^\infty Vrdr$
  - Conservation of Momentum:

$$\frac{d}{ds}\int_0^\infty V^2 rdr = UE\sin(\theta_1)\cos(\theta_2) + \int_0^\infty \frac{g(\rho_\infty - \rho)}{\rho_d} rdr\sin(\theta_2)$$

- Zone of Established Flow:

$$POWER\ PROFILES = \left(1-(\frac{r}{b})^{\frac{3}{2}}\right)^2$$

for concentration, velocity, temperature, width, and geometry to approximate Gaussian Profiles

- Zone of Merging
  - Superimposition of Plume Property Distributions

UDKHDEN Dispersion Model Cont'd

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$$POWER\ PROFILES = \left(1 - \left(\frac{r}{b}\right)^{\frac{3}{2}}\right)^2$$

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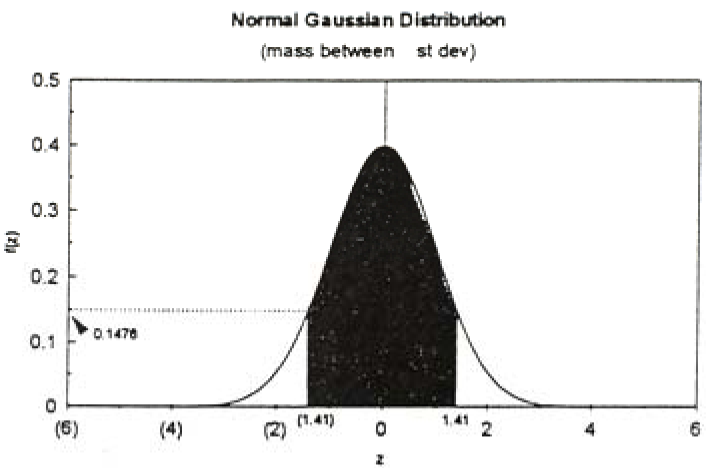
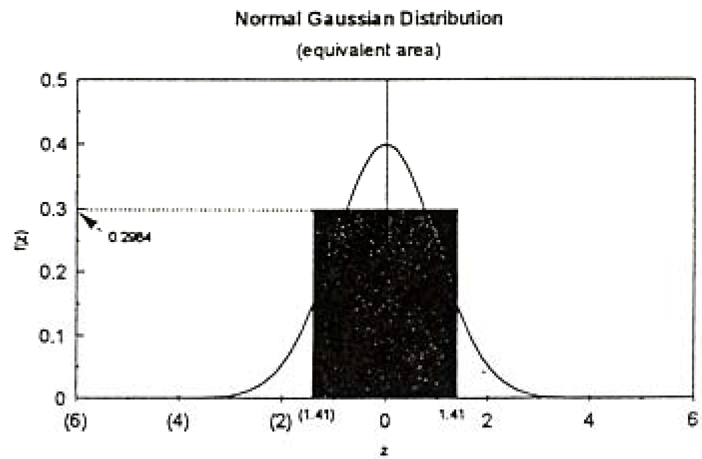
- Zone of Merging
  - Superimposition of Plume Property Distributions

Equivalent Areas ("FAD")





ZID-FAD = CENTERLINE DISPERSION / 0.7481 (+/- 1.41 SIGMA)

TMZ-FAD = CENTERLINE DISPERSION / 0.7909 (+/- 1.25 SIGMA)

Restratification

- For Holley and Jirka (1986) restratification will occur if the densimetric Froude number is less than a critical value:

$$\frac{u_a}{\sqrt{|g'|H}} < 0.6 \; to \; 0.7$$

where:	u_a	**= ambient velocity (ft/sec)**
	$\|g'\|$	**= buoyant acceleration (ft/sec2)**
		= $\|g\,\Delta\rho/\rho_a\|$
	$\Delta\rho$	**= residual density difference between ambient and effluent**
		= $\|\rho_a - \rho\|/S$
	r_a	**= ambient density**
	g	**= acceleration due to gravity (ft/sec^2)**
		= 32.2 ft/sec^2
	S	**= dispersion at the end of the JMZ**
	H	**= water depth (ft)**

Bouyant Spreading Zone Residual Plume Velocity

$$u_i = \frac{2S_iQ_e}{L_DH}$$

where:

u_i	=	Plume velocity at the end of the jet momentum zone (ft/sec)
S_i	=	Dispersion at the end of the jet momentum zone
Q_e	=	Effluent flow in (ft^3/sec)
L_D	=	Diffuser length (ft)
H	=	Local water depth (ft)

Plume velocity at the end of the Jet Momentum Zone (JMZ) during November field study:

S_i	= 88:1 (66 divided by 0.7481)
Q_e	= 14 mgd
	= 21.7 ft^3/sec
L_D	= 100 ft
H	= 15 ft

$$\boxed{\begin{aligned} u_i &= \frac{2(88)(21.7\,ft^3/\sec)}{(100\,ft)(15\,ft)} \\ u_i &= 2.55\,ft/\sec \end{aligned}}$$

For comparison:

Ambient current velocity: 2.38 ft/sec

Port exit velocity: 8 ft/sec

End of Buoyant Spreading Regions
Plume Velocity

$$u = u_i e^{-\phi(x-x_i)} \left[1 + \beta\left[1 - e^{-\phi(x-x_i)}\right]\right]^{-0.5}$$

where:

u = velocity at end of BSZ (ft/sec)

u_i = velocity at end of JMZ (ft/sec)

$\phi = f_o/(8H)$

f_o = Moody friction factor = 0.035

H = local water depth (ft)

$\phi = 0.035 / [8\ (15\ \text{ft})]$

$= 0.000292\ \text{ft}^{-1}$

x = distance downstream from x_i

x_i = distance at end of JMZ (ft)

$\beta = 2a_2/(I_i b_i \phi)$

b = $[2(0.068)]/[(0.8862)(50\ \text{ft})(0.000292\ \text{ft}^{-1})]$

= 10.52

a_2 = entrainment coefficient = 0.068

$I_i = \sqrt{\pi}/2 = 0.8862$

$b_i = 0.5\ L_D = 50$ ft

L_D = diffuser length (ft) = 100 ft

At the end of an intermediate zone: $b = b_i \left[e^{\phi(x-x_i)}(1+\beta) - \beta\right]$

where: **b** = **plume width at end of BSZ (ft)**

b_i = **plume width at end of JMZ (ft)**

At the end of the BSZ: $S = S_i \left[1 + \beta\left(1 - e^{-\phi(x-x_i)}\right)\right]^{-0.5}$

where: **S** = **dispersion at end of BSZ**

S_i = **dispersion at end of JMZ**

Far-field Dispersion

$$c(x,y,z)=\frac{C_0Q_0}{4(z_2-z_1)u(\pi D_y x/u)^{0.5}}*\sum_{n=-\infty}^{n=+\infty}\sum_{m=-\infty}^{m=+\infty}F_1*F_2$$

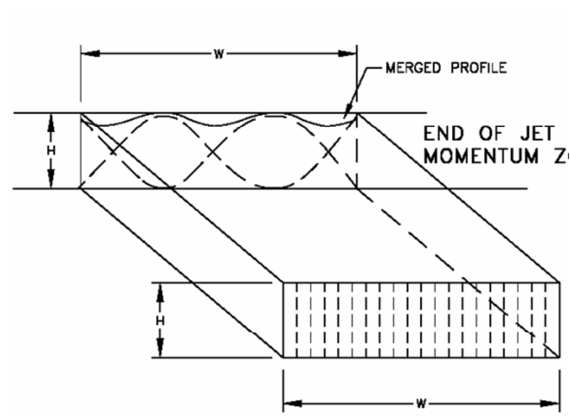
where:

$$F_1=\exp\left[-\frac{(y-y_0-2nB)^2}{4D_y x/u}\right]+\exp\left[-\frac{(y+y_0-2nB)^2}{4D_y x/u}\right]$$

$$F_2=erf\left[\frac{z+z_2-2mH}{2(D_z x/u)^{0.5}}\right]-erf\left[\frac{z+z_1-2mH}{2(D_z x/u)^{0.5}}\right]+erf\left[\frac{z-z_1-2mH}{2(D_z x/u)^{0.5}}\right]-erf\left[\frac{z-z_2-2mH}{2(D_z x/u)^{0.5}}\right]$$

and where: C(x,y,z) = concentration at location x,y,z (units)

x	=	distance downstream from line source (ft)
y	=	distance from channel bank (ft)
yo	=	location of line source from channel bank
z1	=	distance from water surface to top of line source (ft)
z2	=	distance from water surface to bottom of line source (ft)
u	=	ambient river velocity
Dy	=	lateral dispersion coefficient (ft2/s)
	=	bu*/H
b	=	0.23 for long straight channels
u*	=	shear velocity (ft/sec)
	=	3.8 u n / (H)1/6
n	=	Manning's n = 0.035
Dz	=	vertical dispersion coefficient
	=	Dy/3
H	=	river depth (ft)
B	=	river width (ft)
Qo	=	initial source flow (ft3/sec)
Co	=	initial source concentration (units)
erf	=	error function
n, m	=	indices



NOTE: PLANE SOURCE MODELED AS INDIVIDUAL, EQUAL, LINE SOURCES

Jet Momemtum: Unstable Plume Analysis

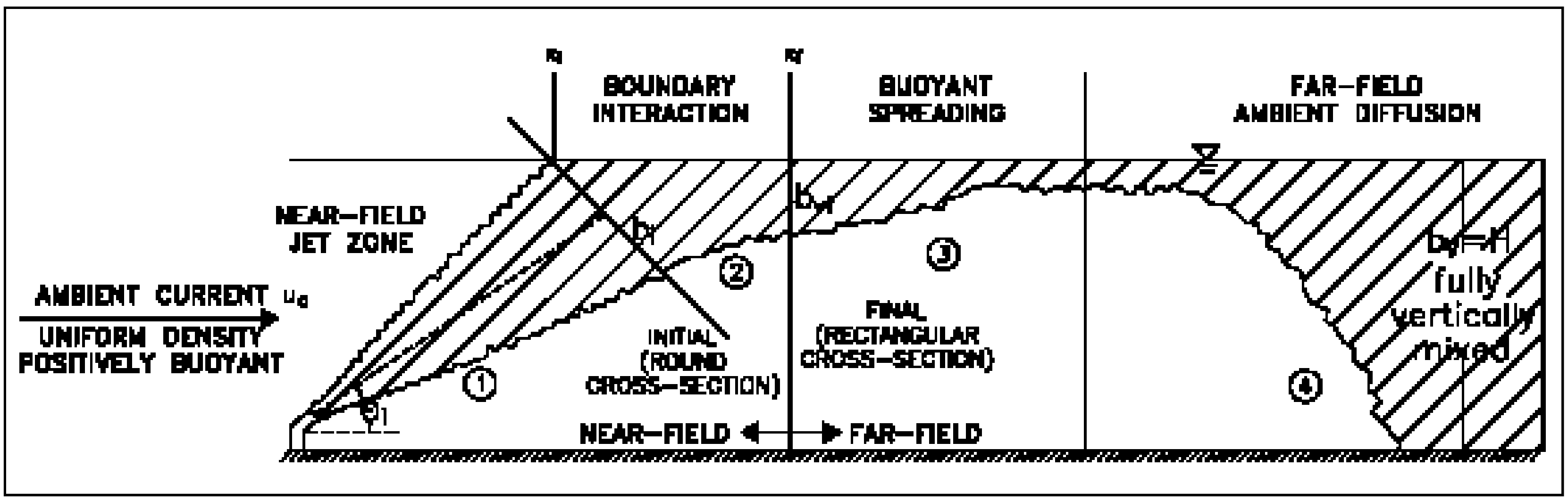
(Shallow Water Diffusers)
Holley and Jirka 1986

$$S = \frac{1}{2}V + \frac{1}{2}\left(V^2 + \frac{2m_o H}{q_o^{\,2}}\cos\theta_o\right)^{0.5}$$

where:

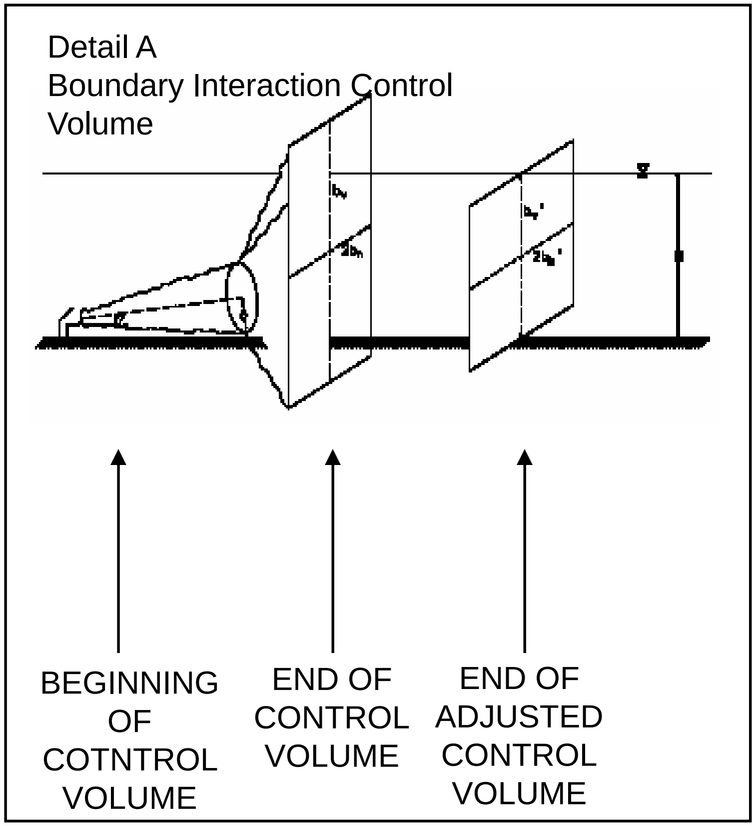
S	= bulk dispersion (___:1, dimensionless)	
V	= volume flux ratio,	
	or ambient mixing due to ambient current	
	= $u_a H/q_o$	
H	= water depth	
q_o	= discharge flux per unit length	
	= $u_o a_o/L$	
m_o	= momentum flux (ft^3/sec^2)	
	= $u_o 2a_o/L$	
L	= port spacing	
a_o	= port area (ft^2)	
u_o	= port exit velocity	
θ_o	= port discharge angle	

CORMIX Schematic for Dispersion From a Diffuser

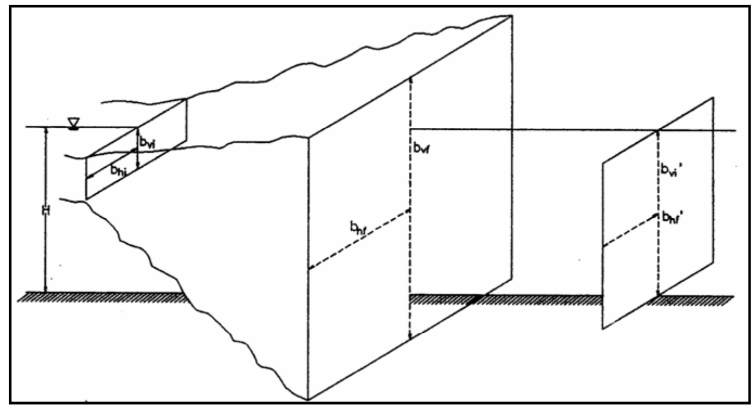


CORMIX Schematic

Near-field Dispersion



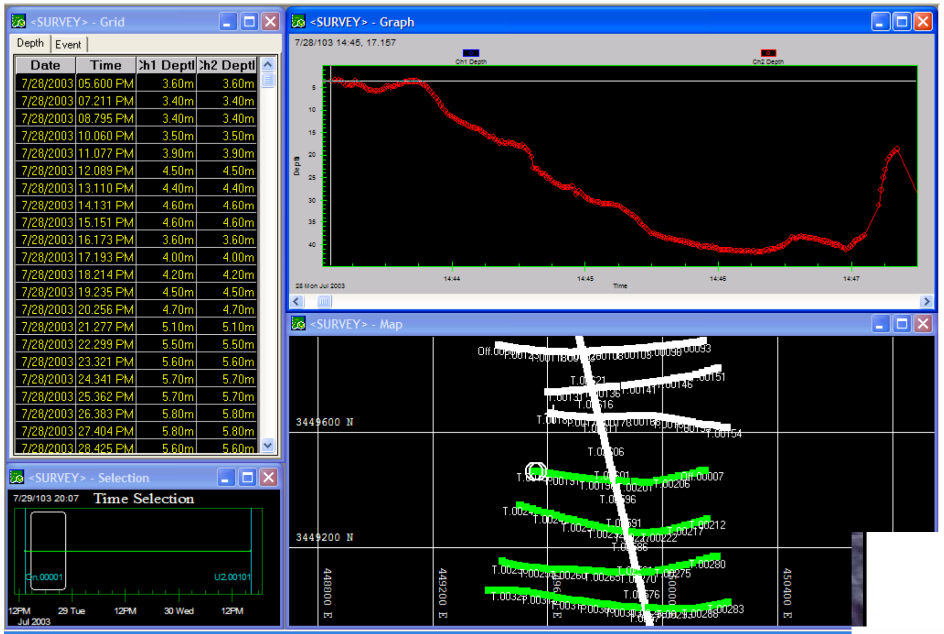
Far-field Dispersion



Data Required for Designing a Diffuser

- Bathymetry
- Effluent and Background Water Quality
- River Stage and Velocity
- Dye Monitoring

Bathymetry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3449200 N
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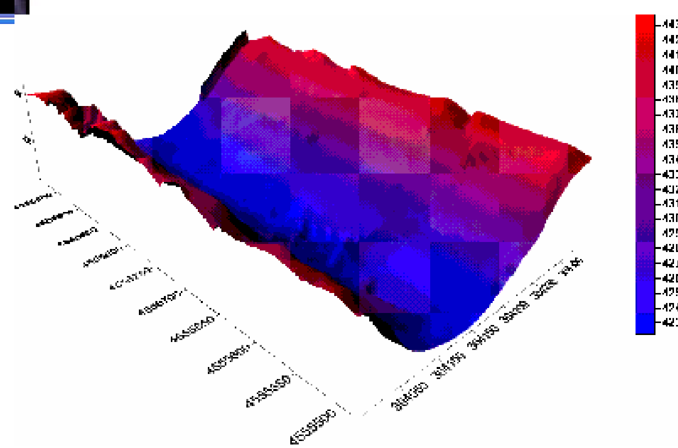
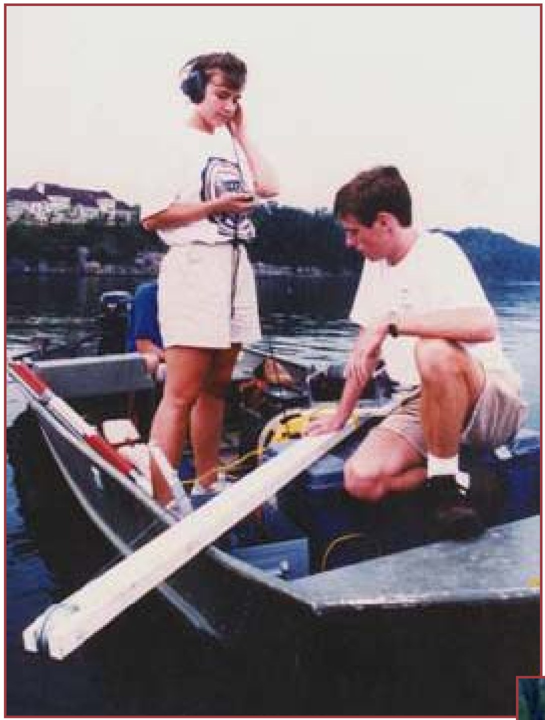
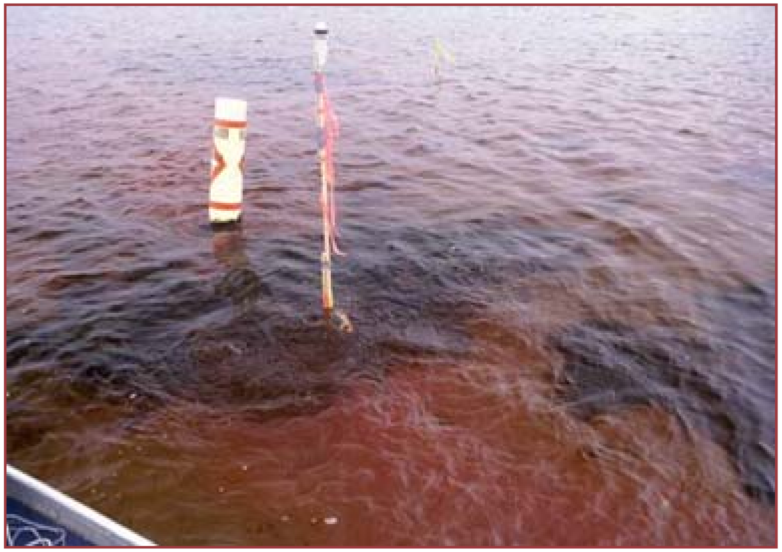
7/29/103 20:07
Time Selection



Discharge/Velocity Measurements



Dye Dispersion



Pump Set Up

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