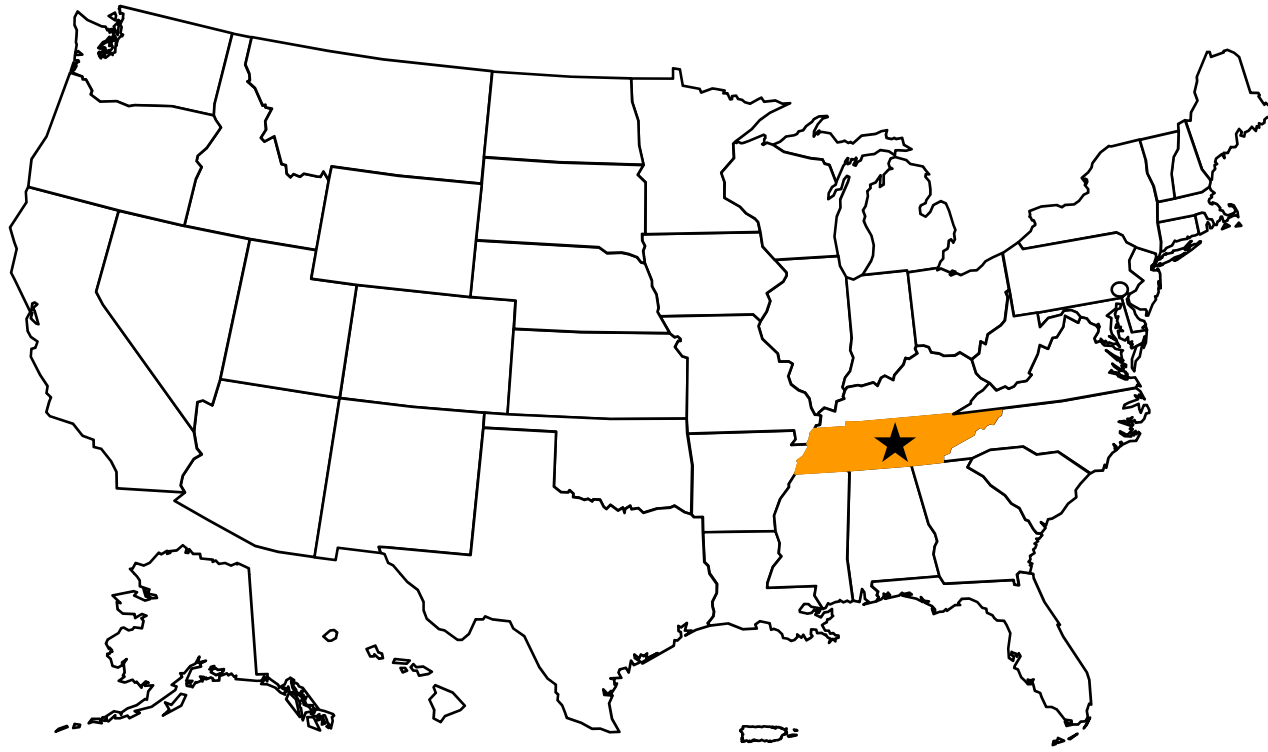# Maximizing Effluent Dispersion and Minimizing Mixing Zones

Water Environment Federation
People to People
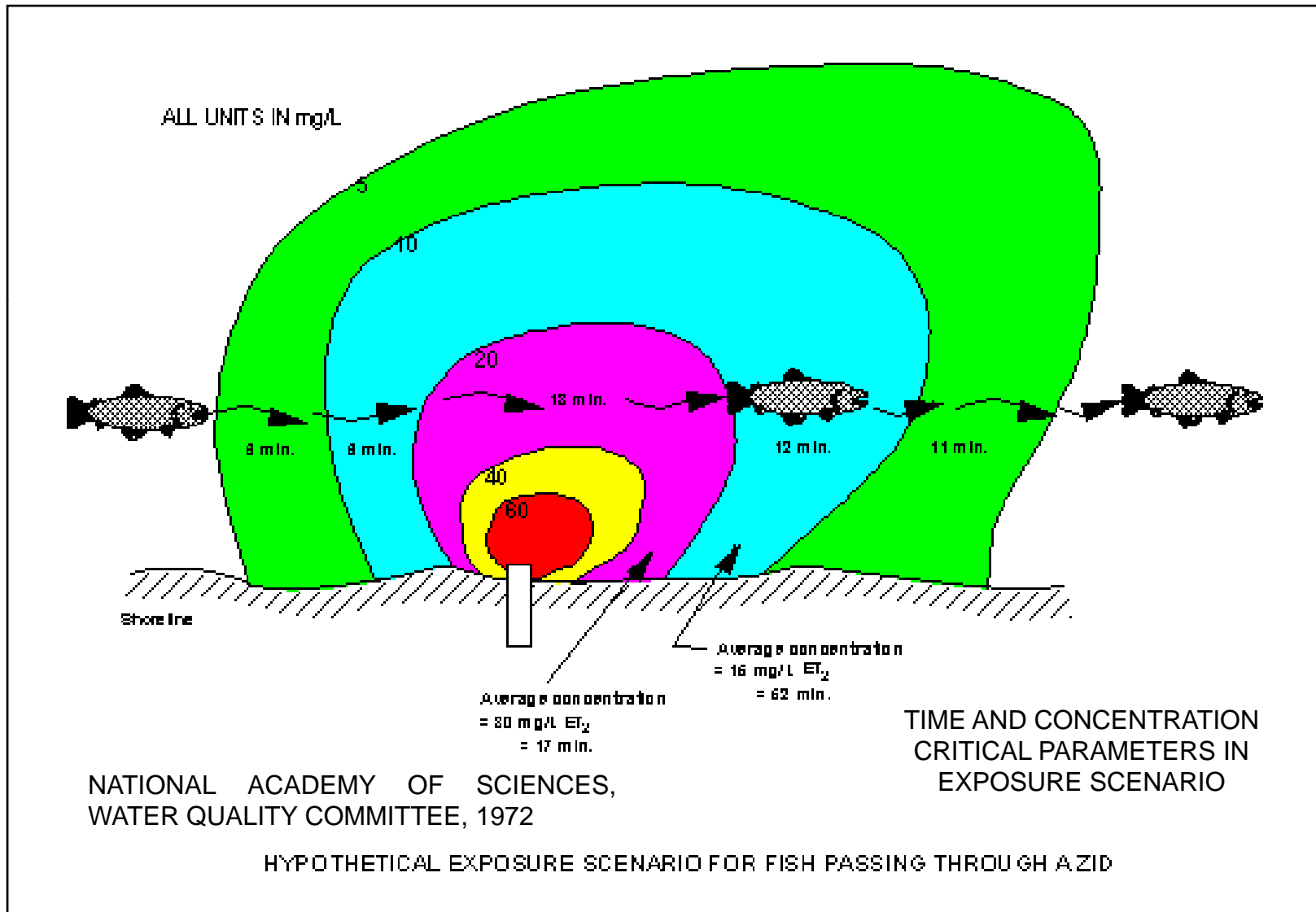### Beijing, China

November 2008

Presented by
Michael R. Corn, P.E.
President, **AquAeTer, Inc.**
Brentwood, Tennessee
USA

AquAeTer

Grand Ole Opry
Home of Country Music

Why Do We Need Mixing Zones?

ALL UNITS IN mg/L

5
10
20
40
60

8 min. | 8 min. | 13 min. | 12 min. | 11 min.

Shore line

Average concentration = 80 mg/L ET₂ = 17 min.

Average concentration = 16 mg/L ET₂ = 62 min.

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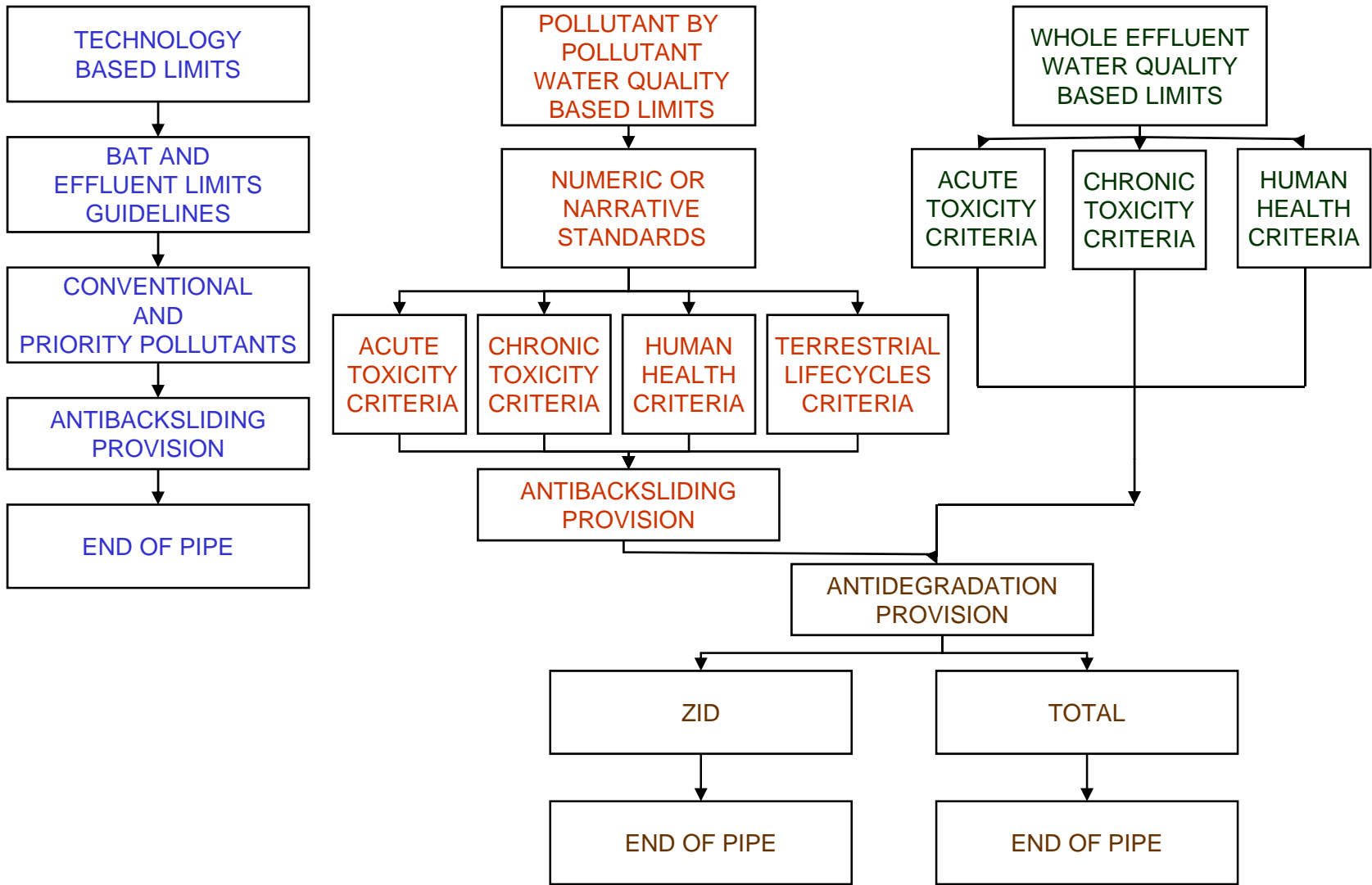
FIGURE 2
CLEAN WATER ACT OF 1987
WATER QUALITY-BASED TOXICS CONTROL

3. Purpose of Mixing Zones

o   Achieve Maximum Dispersion in Smallest Area

o   Minimize Effects on Receiving Water

o   Minimize Acute and Chronic Toxicity in Receiving Stream

o   Meet Narrative Water Quality Standards

o   Provide Maximum Protection for Receiving Stream

o   Maintain Zone of Passage for Fish

o   Meet Local or National Mixing Zone Requirements

o   Meet Technical Guidance

Oregon Guidelines for Mixing Zones

o   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)

o   Shall be free of Nuisance materials

o   Limits shall be described in the wastewater discharge permit.

o   Avoid overlap with other mixing zones

o   Not threaten public health

o   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

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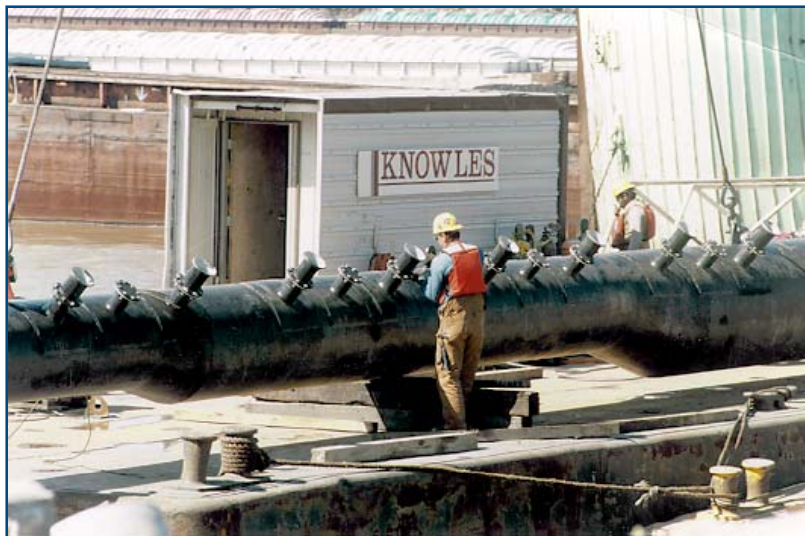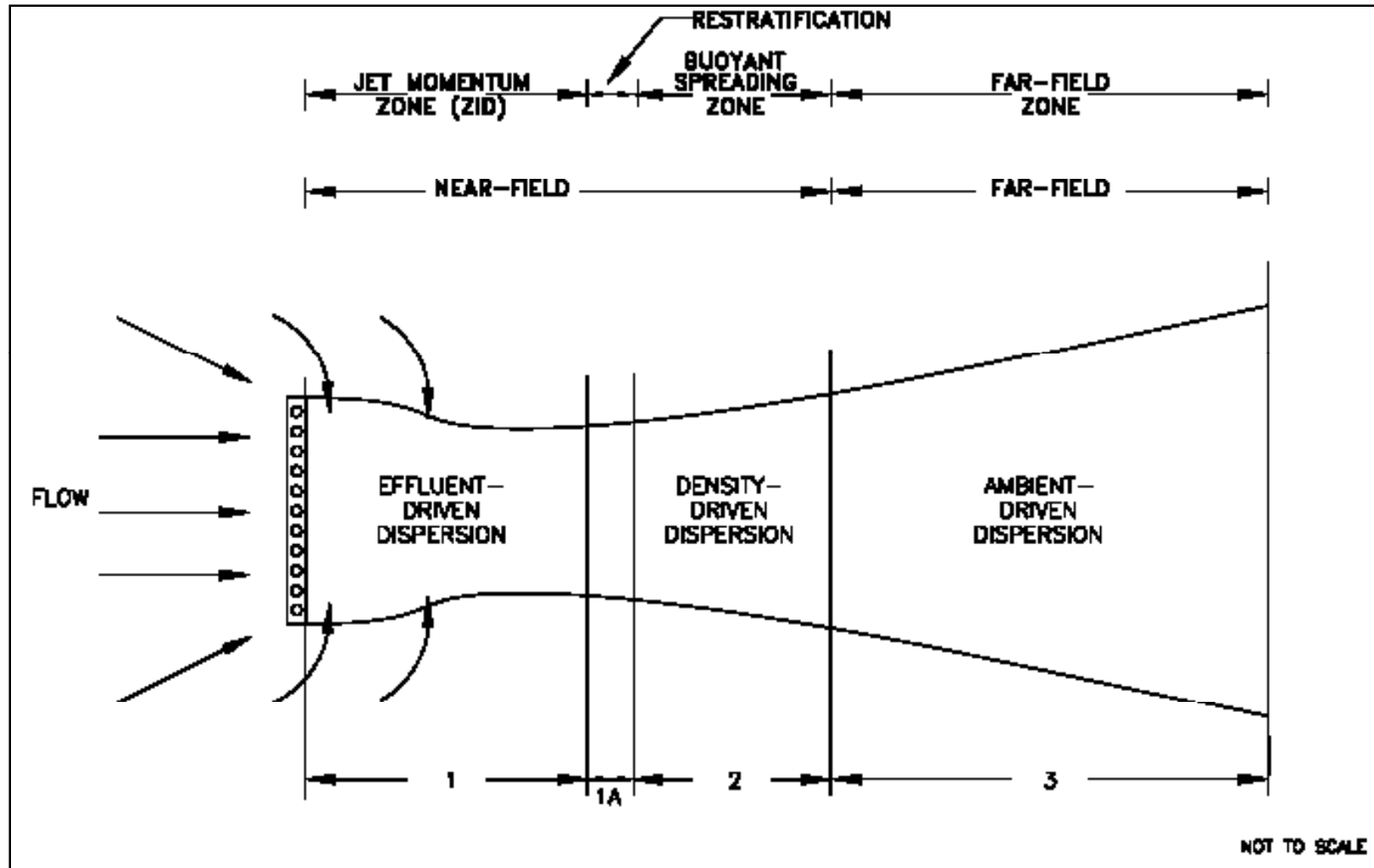
Diffusers

Purpose & Design Considerations

NEED RULES OF THUMB

5. Hydraulic Mixing Zone Concepts

o To Define the Dispersion from Effluent Momentum and Ambient Diffusion

Diffuser Design Considerations

o Effluent Mixing Zone
- Zone of Initial Dilution (ZID)
- Total Mixing Zone

o Enhancement of Mixing
- Side Channel Discharge
- Single-port or Multi-port Diffuser
- Real-time Effluent Discharge (tidal or dynamic flows)

o 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

o 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

o 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)

o   TMZ is Far-field or Ambient Diffusion

o   Far-field technically extends until effluent totally mixed with receiving stream – this may take 13 to 16 km or more

o   No Chronic toxicity must be met at edge of this zone

o   Zone of free passage limits TMZ in U.S. to 25% of cross-sectional area or volume of flow.
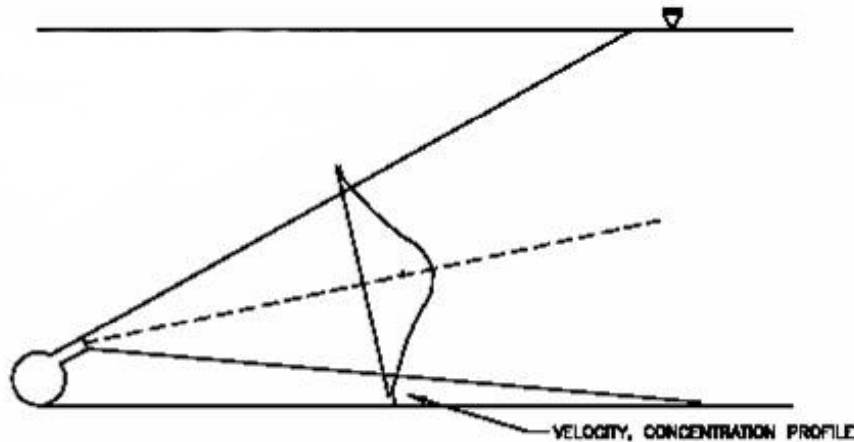
Bulk Dispersion Analysis
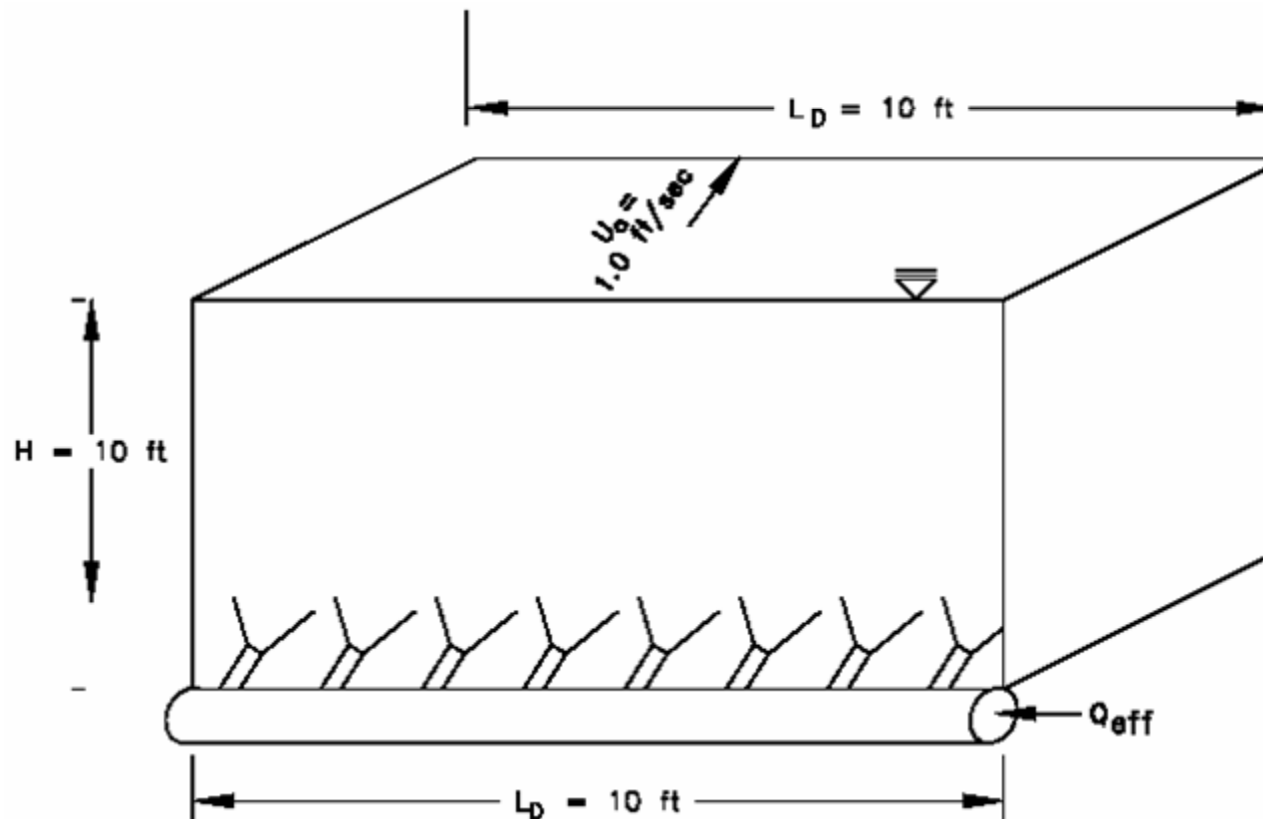
$$\text{ESTIMATE OF DISPERSION} = \frac{(U_o \times H \times L_D) + Q_{eff}}{Q_{eff}} = \frac{(1.0 \text{ ft/sec} \times 10 \text{ ft} \times 10 \text{ ft}) + 5 \text{ cfs}}{5 \text{ cfs}} = \frac{105 \text{ cfs}}{5 \text{ cfs}} = 21:1$$
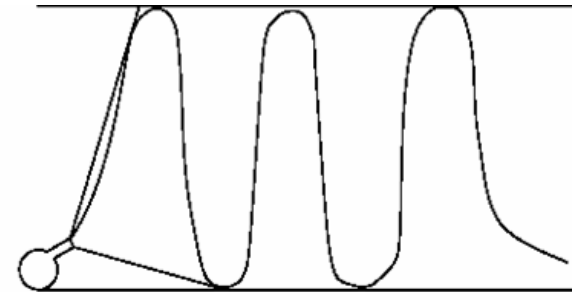
NOT TO SCALE

Plume Stability Analysis

STABLE (GAUSSIAN) PLUME

VELOCITY CONCENTRATION PROFILE

UNSTABLE PLUME

VELOCITY, CONCENTRATION PROFILE

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

Jirka (1982)

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

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

Adams (1982), Jirka (1973,1982)

Jet Zone
Entrainment of Water (1/2 Plume)
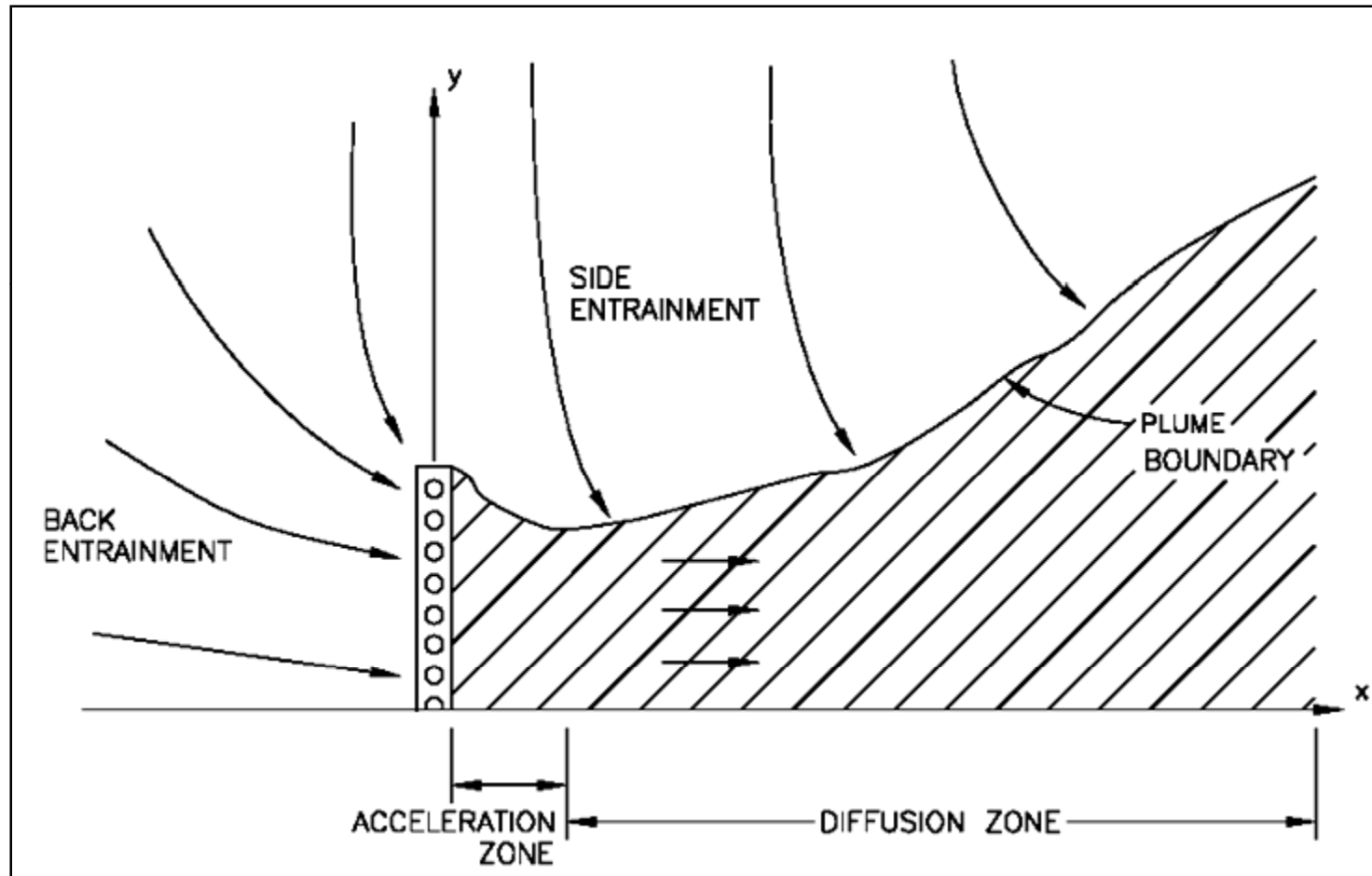
Stable Plume Analysis

(Plan View)

VELOCITY PROFILE

ENTRAINMENT VELOCITY

CENTERLINE TRAJECTORY

b

CONCENTRATION PROFILE

AMBIENT DENSITY

ZONE OF FLOW ESTABLISHMENT

U_0

PORT

(Profile View)

ENTRAINMENT SURFACE

L

MERGED PROFILE
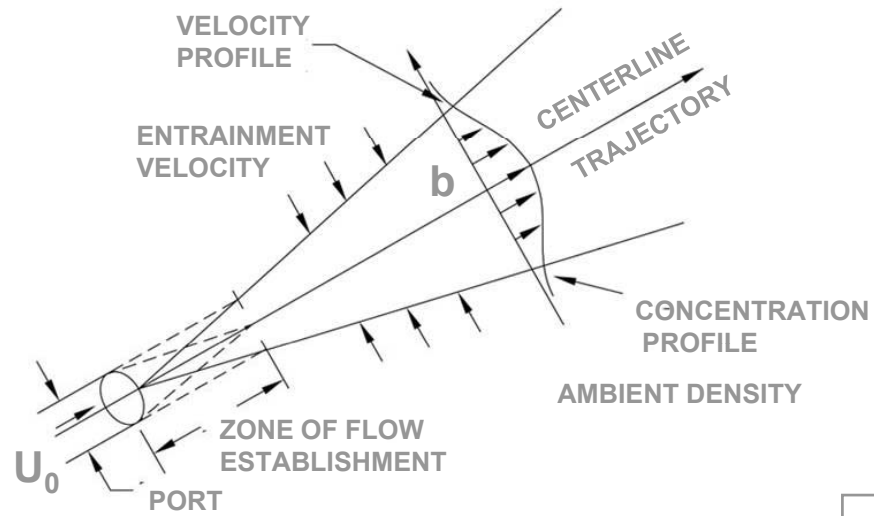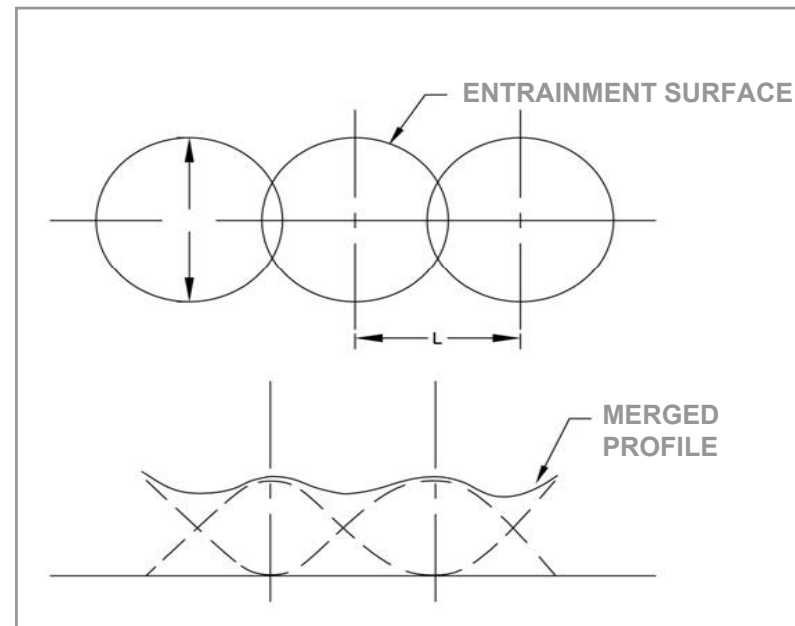
UDKHDEN Dispersion Model Cont'd

o Zone of Flow Establishment

- Conservation of Mass: $\dfrac{d}{ds}\displaystyle\int_0^\infty Vr\,dr = E$

- Conservation of Energy: $\dfrac{d}{ds}\displaystyle\int_0^\infty V(T-T_\infty)r\,dr = -\dfrac{dT_\infty}{ds}\displaystyle\int_0^\infty Vr\,dr$

- Conservation of Pollutant: $\dfrac{d}{ds}\displaystyle\int_0^\infty V(C-C_\infty)r\,dr = -\dfrac{dC_\infty}{ds}\displaystyle\int_0^\infty Vr\,dr$

- Conservation of Momentum:

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

o 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

o Zone of Merging

- Superimposition of Plume Property Distributions
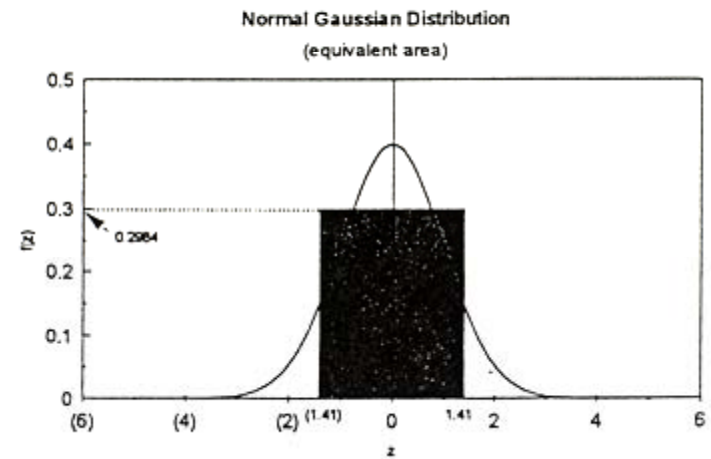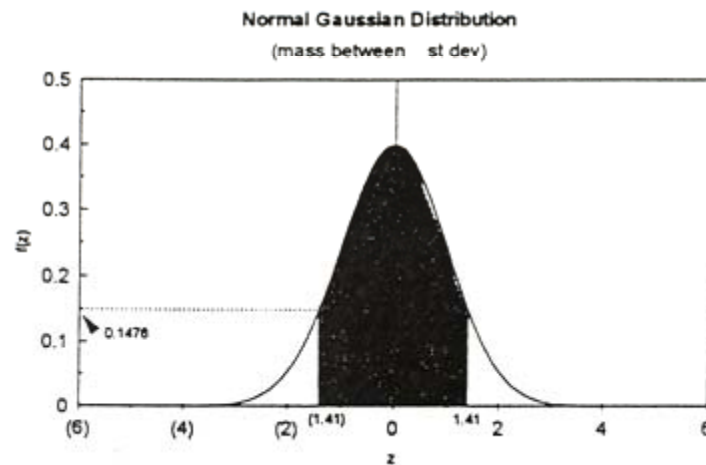
UDKHDEN Dispersion Model Cont'd

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

o 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

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

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

where:

u_a	= ambient velocity (ft/sec)	
$\left| g^{'} \right|$	= buoyant acceleration (ft/sec2)	
	$= \left| g \, \Delta\rho/\rho_a \right|$	
$\Delta\rho$	= residual density difference between ambient and effluent	
	$= \left| \rho_a - \rho \right| /S$	
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

$$u_i = \frac{2S_i Q_e}{L_D H}$$

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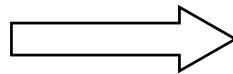
$$u_i = \frac{2(88)(21.7\,ft^3/\sec)}{(100\,ft)(15\,ft)}$$
$$u_i = 2.55\,ft/\sec$$

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)

ϕ = $f_o/(8H)$

f_o = Moody friction factor = 0.035

H = local water depth (ft)

ϕ = 0.035 / [8 (15 ft)]

= 0.000292 ft^{-1}

x = distance downstream from x_i

x_i = distance at end of JMZ (ft)

β = $2a_2/(l_i b_i \phi)$

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

= 10.52

a_2 = entrainment coefficient = 0.068

l_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

$$c(x, y, z) = \frac{C_0 Q_0}{4(z_2 - z_1)u(\pi D_y x / u)^{0.5}} * \sum_{n=-\infty}^{n=+\infty} \sum_{m=-\infty}^{m=+\infty} F_1 * F_2$$
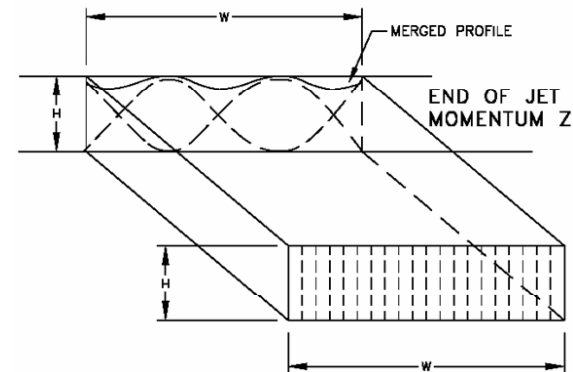
where:

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

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

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

W — MERGED PROFILE

END OF JET MOMENTUM ZONE

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

Jet Momemtum: Unstable Plume Analysis
(Shallow Water Diffusers)
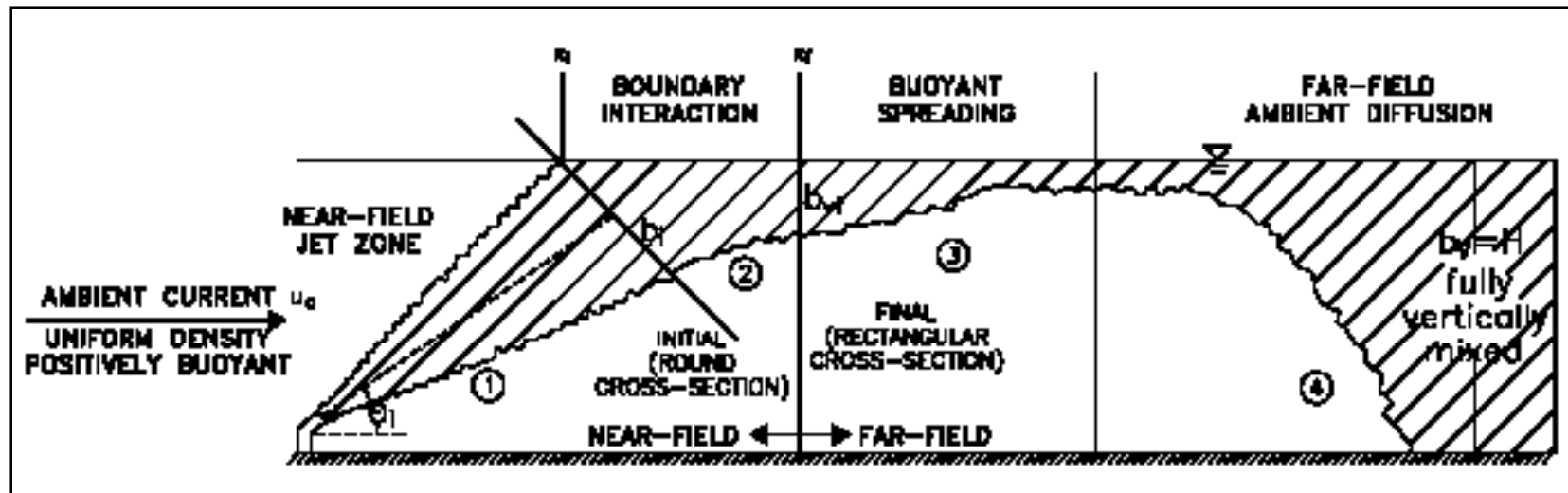## Holley and Jirka 1986

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

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 (ft³/sec²)
	= $u_o 2a_o/L$
L	= port spacing
a_o	= port area (ft²)
u_o	= port exit velocity
θ_o	= port discharge angle

CORMIX Schematic for Dispersion From a Diffuser
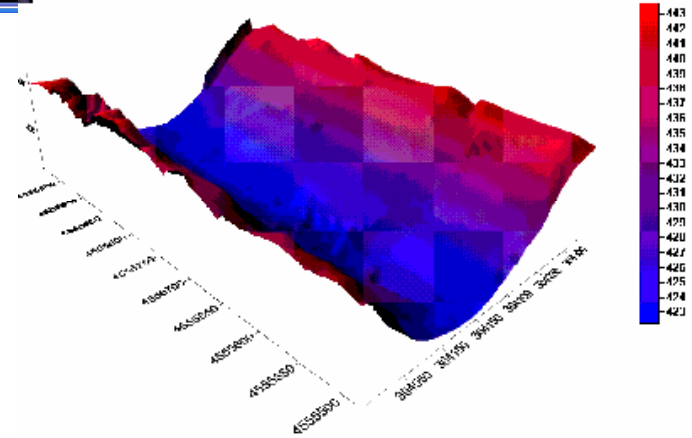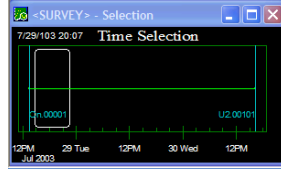
CORMIX Schematic

Near-field Dispersion
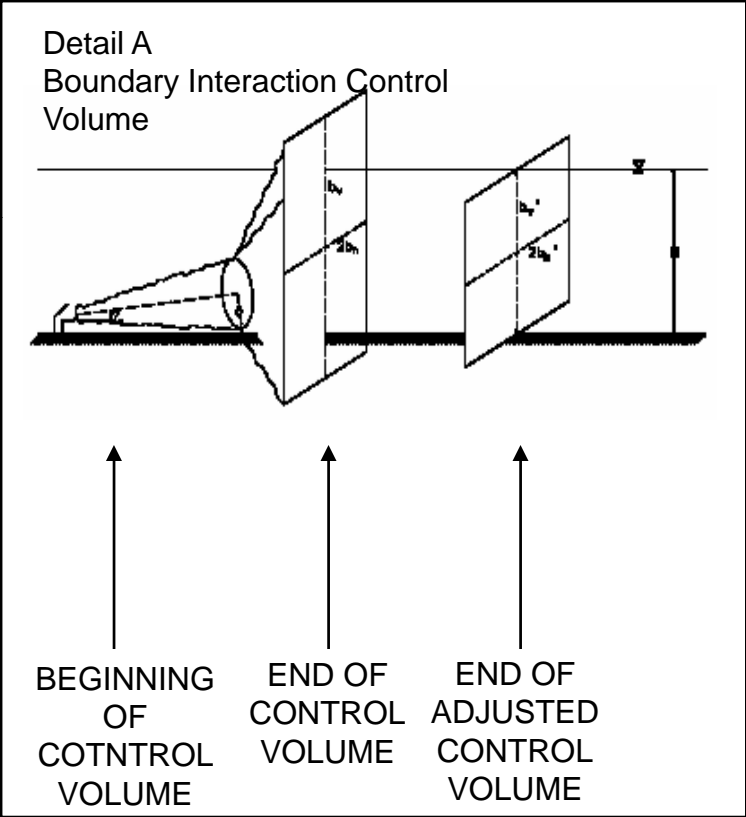
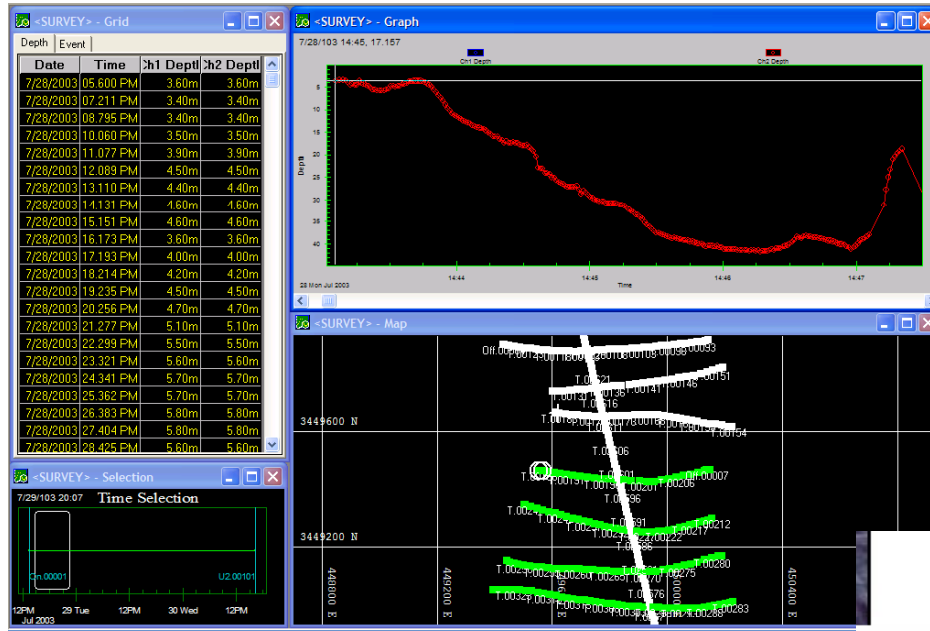## Far-field Dispersion
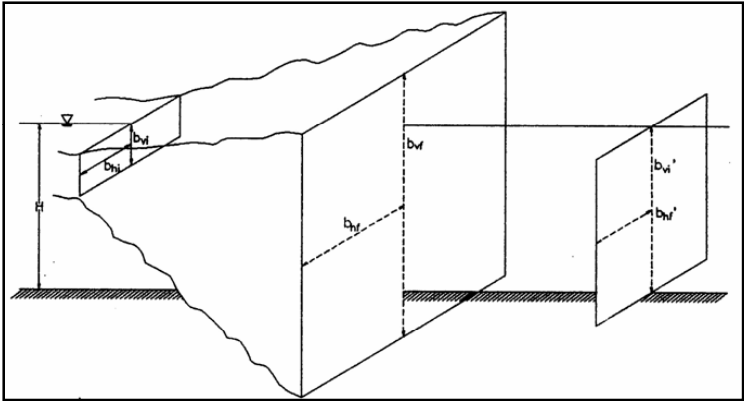
Data Required for Designing a Diffuser

o   Bathymetry

o   Effluent and Background Water Quality

o   River Stage and Velocity

o   Dye Monitoring

Bathymetry

Discharge/Velocity Measurements

Dye Dispersion

Pump Set Up

AquAeTer, Inc.

optimizing environmental resources – water, air, earth

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