Mixing Zone Modeling Webinar Workshop Series
January 22- 24 2013

Science of Mixing

Presentation by
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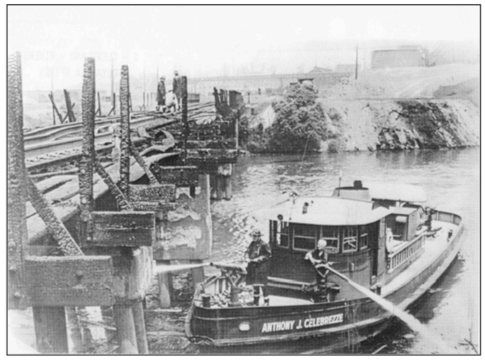
Science of Mixing - Outline

- Part 1
  - Regulatory Background
  - Mixing Zones (MZ)
  - Q & A
- Break (10 minutes)
- Part 2
  - Initial mixing conditions
  - Physical mixing processes
  - Examples of environmental mixing processes
  - Q & A

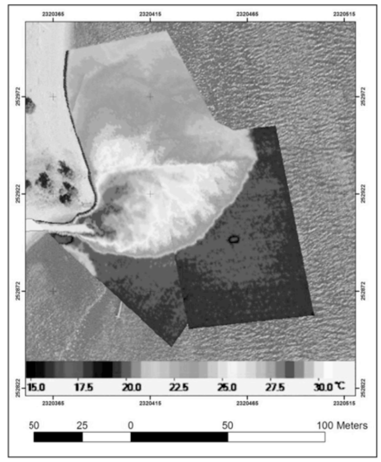
Science of Mixing - Part 1: Regulatory Background



Zeitgeist in Water Quality Management:
The Cuyahoga River in Ohio On Fire!

Section Outline

- Water Quality (WQ) Management
  - Motivation
- Legislation
  - Clean Water Act (CWA)
- Regulatory WQ Standards
  - Ambient WQ Standards
  - Discharge Standards
- Mixing Zones (MZ)
  - Toxic Discharges
    - Special Restrictions
  - Guidance documents



Aerial Infrared (IR) Image of a Thermal Discharge Mixing Zone.

Federal Water Pollution Control Legislation

- Federal Water Pollution Control Act 1948
- Water Pollution Control Act of 1956
- Federal Water Pollution Control Amendments (1961)
- Water Quality Act of 1965
- Water Quality Improvement Act of 1970
- Federal Water Pollution Control Amendments (1972)
- Clean Water Act of 1977
- Municipal Wastewater Treatment Plant Construction Grants Amendment (1981)
- Water Quality Act of 1987

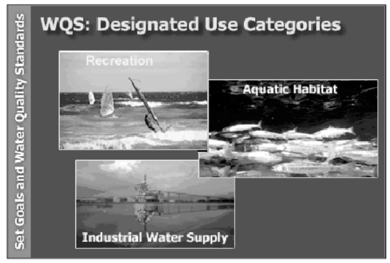
Federal Water Pollution Control Act - 1972

WQ Management:

- Federal Gov't Assumes Responsibility

Goals:

- "***Fishable*** & ***Swimmable***" waters
- ***Eliminate*** discharge of pollutants
- Set WQ Standards - ***Designated Use***



Features:

- **N**ational **P**ollutant **D**ischarge **E**limination **S**ystem permits (**NPDES**)
- **B**est **P**racticable **T**echnology (***BPT***)
- **B**est **A**vailable **T**echnology (***BAT***)
- Effluent limitations
- WQ standards

NPDES Permitting

NPDES Permits: Elements

- Effluent limits
- Best management practices
- Compliance schedules
- Monitoring requirements
- Reporting requirements
- Standard Conditions- Reopener, etc.
- For POTWs only: Pretreatment program and sludge management requirements

Clean Water Act (CWA - 1977)

Pollutant Classification:

1. **Conventional**
   – BOD, pH, TSS, fecal coliforms, oil and grease
2. **Toxic**
   – heavy metals – copper, lead, nickel;
   – organic chemicals – benzene, chloroform
3. **Non-conventional**
   – COD, ammonia

7. **Heat**
8. **Dredge, Sediments & fill spoils**

Effluent Limitations:

1. **Best Conventional Technology** (BCT)
   – Limitations required for conventional pollutants
2. **Best Available Technology** (BAT)
   – Limitations required for toxic and non-conventional pollutants

Water Quality Standards and Criteria

Water Quality Standards:

- WQ-based control program
  - Foundation of CWA
- Defines WQ goals
  - Designated use
  - Setting criteria

Water Quality Criteria:

- Numeric criteria
  - Pollutant concentration limits
- Protect aquatic life
- Protect human health

Apply Antidegradation

WQS: The Process

- WQS established by states/territories/authorized tribes
- EPA must review/approve prior to becoming effective
- If EPA disapproves a state/territory/tribe WQS and state/territory/tribe doesn't revise it, EPA promulgates a WQS
- Public review and comment at state/tribe/territory and federal levels (if EPA promulgates)
- States, territories, and authorized tribes must review its WQS every three years and submit to EPA

Set Goals and Water Quality Standards

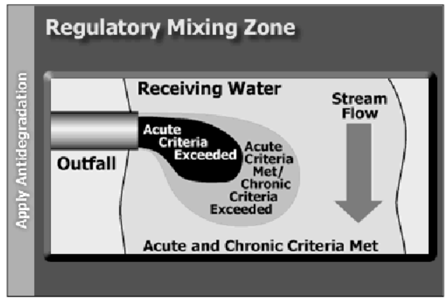
WQC: Examples

WQC	Designated Use	
	Freshwater AL	Marine AL
Copper (acute)	18 ug/L	3 ug/L
Cadium (acute)	4 ug/L	43 ug/L
Cadium (chronic)	1 ug/L	10 ug/L
Chromium (+3) (acute)	1,700 ug/L	10,300 ug/L
Chromium (+6) (acute)	16 ug/L	1,100 ug/L

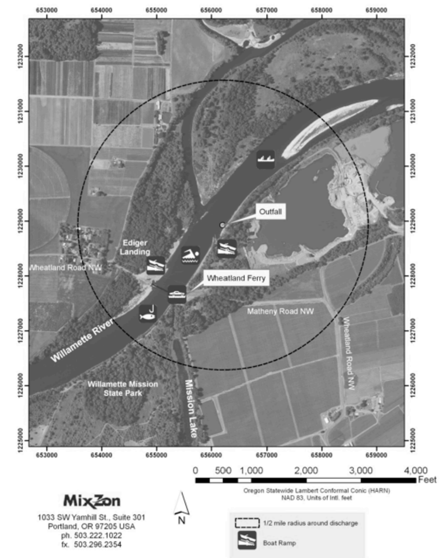
* AL = aquatic life

Mixing Zone Defined

- "An ***allocated impact zone***" where numeric criteria can be exceeded as long as acutely toxic conditions are prevented
- "A ***limited area or volume*** of water where initial dilution of a discharge takes place"
- Water quality criteria apply ***at the boundary*** of the mixing zone, not in the mixing zone itself
- **Environmental Mapping**
  - Resource relationship to mixing zone

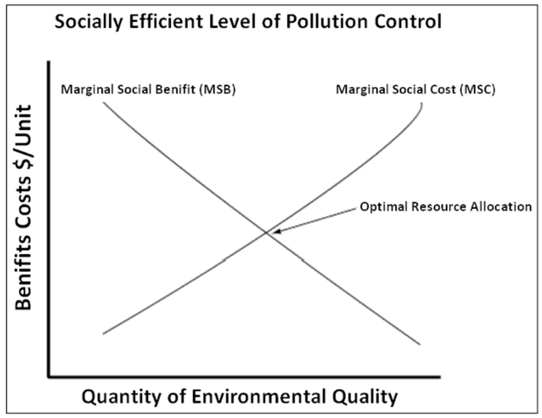


Environmental Mapping



Mixing Zone Motivation & Justification

- High marginal costs of wastewater treatment
- Natural assimilative capacity of the environment
  - "Ecosystem service"
  - Renewable
- Economically efficient



USEPA Mixing Zone Recommendations

Size

- "The area or volume of an individual zone or group of zones be limited to an area or volume as small as practical that will not interfere with the **designated uses** or with the established community of aquatic life"

Shape

- "The shape of a mixing zone should be a simple configuration that is easy to locate in a body of water and avoids impingement on biologically important areas"
- "Shore hugging plumes should be avoided"

USEPA Mixing Zone Recommendations

In-Zone Quality

"A mixing zone ***should be free*** of the following:

1. Materials in concentrations that will cause **acute toxicity** to aquatic life;
2. Materials in concentrations that **settle** to form **objectionable deposits**;
3. Floating **debris, oil scum** and other matter in concentrations that **form nuisances**;
4. Substances in concentrations that produce objectionable **color, odor, taste** or **turbidity**; and
5. Substances in concentrations which produce **undesirable aquatic life** or result in a dominance of **nuisance species**"

Mixing Zone Human Health Protection

- Mixing zones should not result in ***significant health risks*** when evaluated using ***reasonable assumptions*** about ***exposure pathways***.
- ***No overlap*** with drinking ***water intakes***
- ***No significant health risk*** to the average consumer
- Should ***not encroach*** on areas often used for ***fish harvesting*** particularly of stationary species such as ***shellfish***
- May be denied to compensate for uncertainties
- Should ***avoid attraction***

Photo: MixZon Inc. - Mixing Zone study in progress.

State Mixing Zones

- EPA allows the use of a mixing zone except where prohibited by state regulations
- 48 states allow some form of mixing zones
- Mixing zones can be defined as:
  - Lengths
  - Areas
  - Volumes
- For streams and rivers
  - ***Width***, ***cross-section excess, lengths***
- For lakes, estuaries, and coastal waters
  - ***surface area*** affected
- If no specific mixing zone dimensions are given
  - ***case-by-case*** basis
- Often mixing zones ***are negotiated***

Photo: Steve Schnurbusch (ODEQ)

Multiport Diffuser Construction

Mixing Zones: USEPA & State Roles

- **States decide**
  - *To allow Mixing Zones or Not*
  - Policy consistent with CWA
  - Approval by EPA Administrator
- State WQ standards should describe
  - methodology for determining ***location, size, shape, outfall design, and in-zone quality of mixing zones***

Examples: State Regulatory Mixing Zones

State	Water body	Dimensions
Alabama	0	0
Arkansas	large streams	<= 1/4CS
Alaska	rivers, streams lakes	<=1/3 CS <=10% SA
Arizona	NR	NR
California	0	0
Connecticut	streams	<=1/4 CS
Delaware	streams lakes	<=1/3 CS <=10% SA
D.C.	estuary	<=10% SA
Michigan	streams Lake Michigan	<= 1/4 CS <= 1000' radius
W. Virginia	Warm water fish Streams Cold water fish Streams	<= 33% Cs, length <= 10*width <= 20% Cs, length <=5*width

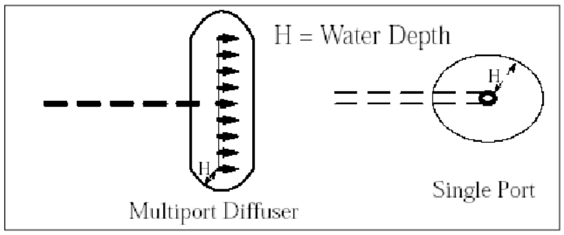
0 => not listed; CS => cross-sectional area; SA => surface area; NR => no reference

Source: Draft Technical Guidance Manual for the Regulations Promulgated Pursuant to Section 301(g) (USEPA 1984)

Mixing Zones: Coastal Waters

- Special regulations
  - Disposal of municipal wastewater into coastal ocean
  - Section 301(h) of Clean Water Act

- Mixing Zone = "***Zone of Initial Dilution***"
  - Must be regularly shaped (circle or rectangle)
  - Must surround discharge structure
  - Must encompass regions exceeding standards under design conditions
  - Dimensions usually given by water depth (H) at discharge (both conventional and toxic pollutants)



Special Mixing Zones for Toxic Substances

USEPA has two water quality criteria for allowable concentrations in toxic discharges:

- ***Criterion Maximum Concentration*** (CMC)
  - Protective of **acute** or lethal effects
  - Spatially restrictive
- ***Criterion Continuous Concentration*** (CCC)
  - Protects against **chronic** effects
  - Similar to a regular ***water quality standard***
  - Must be met at edge of mixing zone
- The acute to chronic ratio (ACR) is:
  - ACR = CMC/CCC; approximately 10 to 100

Toxic Dilution Zone

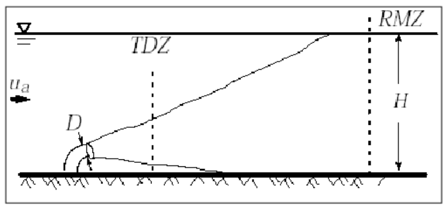
CMC must comply with one of four conditions:

1. Meet CMC within discharge pipe
2. Exit velocity must exceed 3 m/s (10 ft./s)
   - Typical of modern designs
   - Not exclusive (bottom interaction)
3. Geometric restrictions
4. Show drifting organism will be exposed to CMC for less than
   - 1 hour average
   - no more than once every 3 years

Geometric Restrictions: CMC

1. Meet CMC within 10% of distance from edge of outfall structure to edge of RMZ in any direction

3. CMC met within 50 times ***discharge length scale*** (L_Q) in any direction
   – L_Q= square root (cross sectional area discharge outlet);
   – applies to each port of multiport discharge
4. CMC met within distance of 5 times the local ***water depth (H)*** in any horizontal direction
   – H = natural depth before outfall installation under mixing zone design conditions (e.g., ${}_1Q_{10}$ for rivers)
   – Restricts installations in shallow environments or close to shore



Recent EPA Policy on Mixing Zones

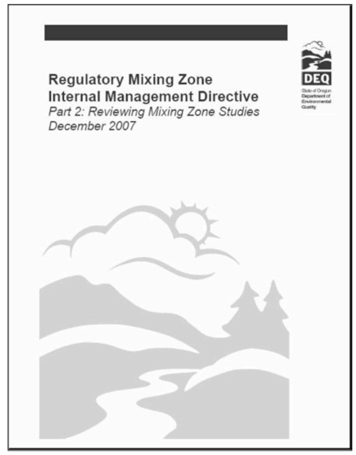
- Great lakes Initiative 2000
- Outlines persistent or Bioaccumulative Chemicals of Concern (BCC)
- Bans new sources
- Phase out over 10 year period for existing sources
- *Ref: http://water.epa.gov/scitech/swguidance/standards/mixingzones/topics.cfm*

Bioaccumulative Chemicals of Concern (BCC)

Lindane	Mirex
Hexachlorocyclohexane (BHC)	Hexachlorobenezene
alpha-Hexachlorocyclohexane	Chlordane
beta-Hexachlorocyclohexane	DDD
delta-Hexachlorocyclohexane	DDT
Hexachlorobutadiene	DDE
Photomirex	Octachlorostyrene
1,2,4,5-Tetrachlorobenzene	PCBs
Toxaphene	2,3,7,8-TCDD
Pentachlorobenzene	Mercury
1,2,3,4-Tetrachlorobenzene	Dieldrin

Guidance on Mixing Zones

- EPA's current mixing zone guidance
  - Technical Support Document for Water Quality-based Toxics Control (USEPA 1991)
  - Water Quality Standards Handbook: Second Edition (USEPA 1994)
- Oregon DEQ IMD
  - Part 1: Allocating Regulatory Mixing Zones
  - Part 2: Reviewing Mixing Zone Studies
  - Fact Sheet: RMZ IMD
  - Memo: Implementing Oregon's RMZ IMD
  - *http://www.deq.state.or.us/wq/pubs/pubs.htm#imds*
- Offshore Oil & Gas NPDES Permit
  - Draft of updated permit released in 2012
  - *http://www.epa.gov/region6/6en/w/offshore/home.htm*



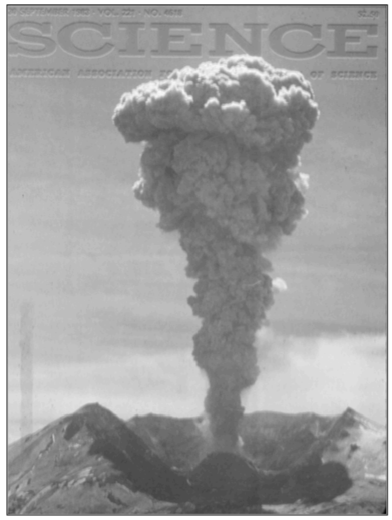
Part 1 - Section Summary

- Water quality issues
- Clean water act standards
- Assimilative Capacity
- Mixing Zones
  - Definition
  - Requirements for conventional and toxic discharges
  - Guidance Documents
- Q & A

Break

10 minute break

Science of Mixing - Part 2: Physical Mixing Processes



Mt. St. Helens: Mother Nature's Version of Buoyant Jet Mixing

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Section Outline

- Initial mixing conditions
- Description of physical mixing processes
  - Near-field mixing
  - Boundary interaction
  - Far-field mixing
- Examples of environmental mixing processes

Initial Mixing Conditions

Mixing is an interplay of ambient and discharge conditions.

Ambient Conditions:

- **Geometry**
  - shallow vs. deep; bounded vs. unbounded
- **Velocity field**
  - bottom roughness, turbulence, tides, etc.
- **Density field**
  - temperature, salinity effects, stratification

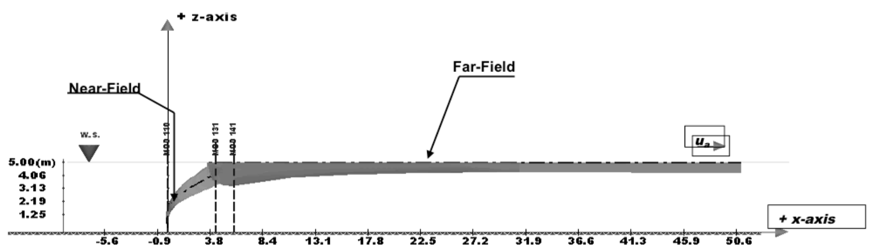
Initial Mixing Conditions

Discharge Conditions:

- **Geometry**
  - Submerged; Near Surface; Above Surface discharge
  - Single port, Multiport, Surface
- **Volume Flux**
  - Mass of pollutant discharge (Q_0) to available dilution water (QA)
- **Momentum Flux**
  - "Intensity" of discharge (u_0 vs. u_a)
- **Buoyancy Flux**
  - Positive, negative, or neutral (ρ_0 vs. ρ_a)

Near-field vs. Far-field Mixing

- **Near-field mixing**
  - **Source properties dominate mixing** (Close to discharge source)
  - Region of "buoyant jet mixing"
  - Time scales of secs to mins; Space scales of 1 m to 100 m
- **Boundary Interaction**
  - **Provides transitions from near-field to far-field mixing**
- **Far-field mixing**
  - Ambient conditions dominate mixing
  - Time scales of mins to hrs; Space scales of 10 m to 1000 m



CorVue Plume Visualization - Side View

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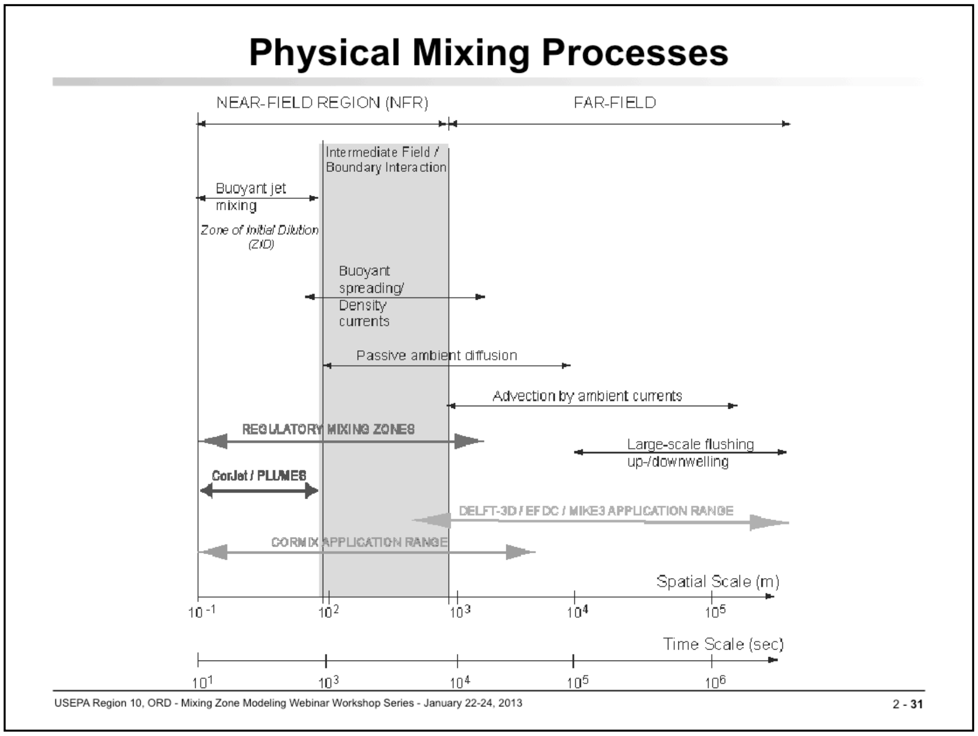

Physical Mixing Processes
NEAR-FIELD REGION (NFR)
FAR-FIELD
Intermediate Field / Boundary Interaction
Buoyant jet mixing
Zone of Initial Dilution (ZID)
Buoyant spreading/ Density currents
Passive ambient diffusion
Advection by ambient currents
REGULATORY MIXING ZONES
Large-scale flushing up-/downwelling
CorJet / PLUMES
DELFT-3D / EFDC / MIKE3 APPLICATION RANGE
CORMIX APPLICATION RANGE
Spatial Scale (m)
Time Scale (sec)
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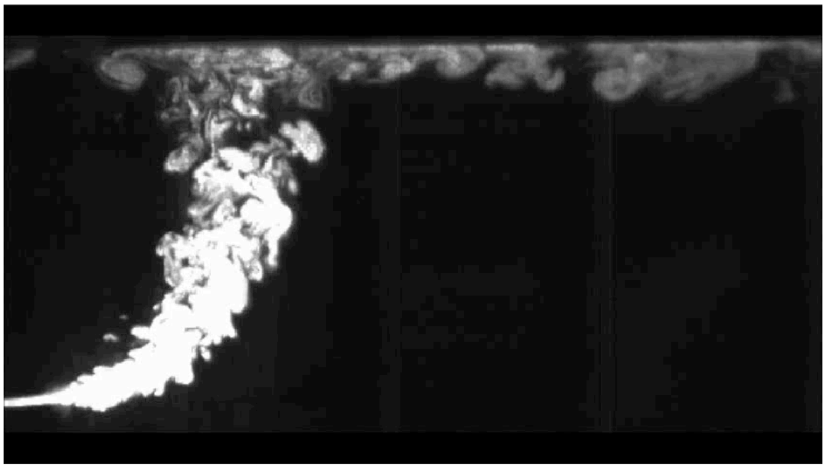
Example of Mixing Process



Video Source: P. Roberts, GA Tech

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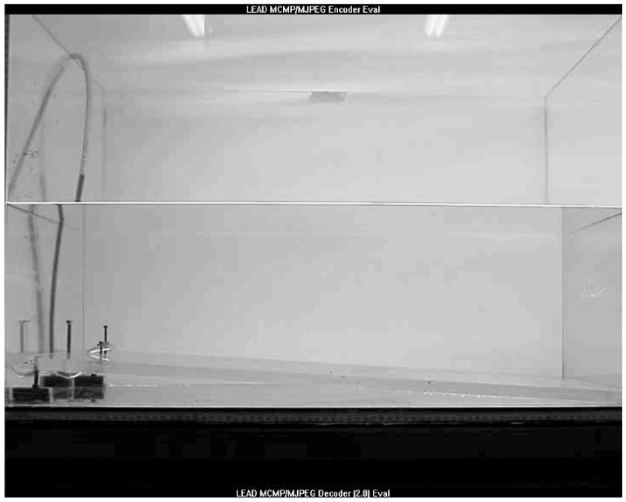
Example of Mixing Process



Video Source: Dr. Gerhard Jirka, Dr. Tobias Bleninger

IFH University of Karlsruhe

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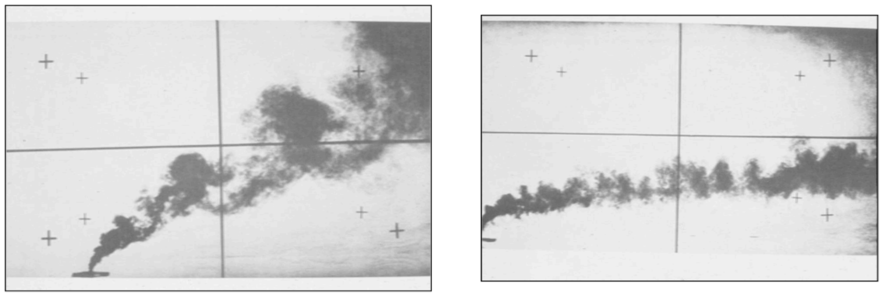

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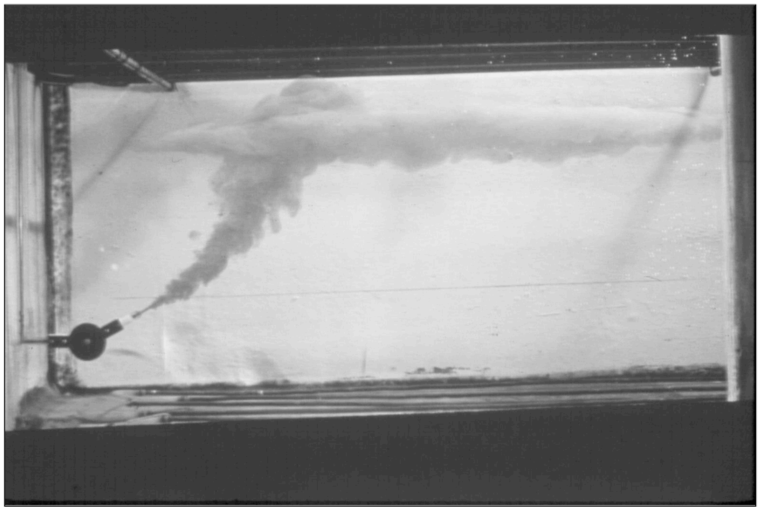
Example of Mixing Process



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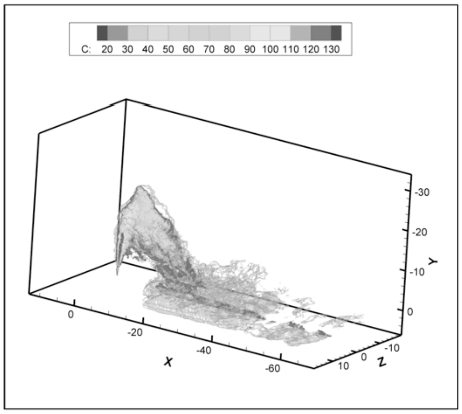
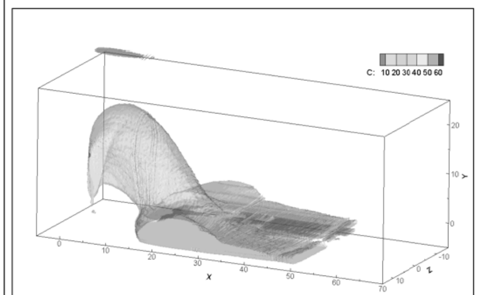
Example of Mixing Process

Example of Mixing Example





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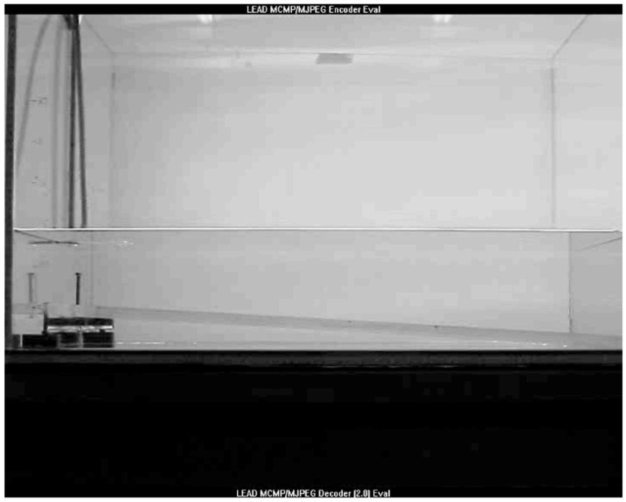

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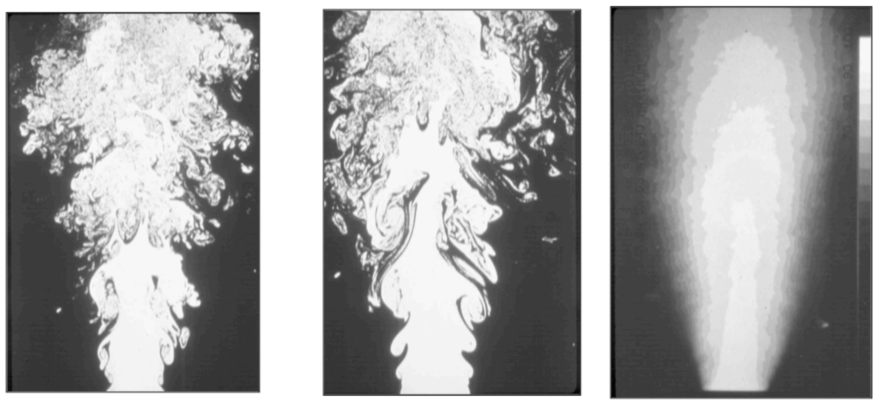

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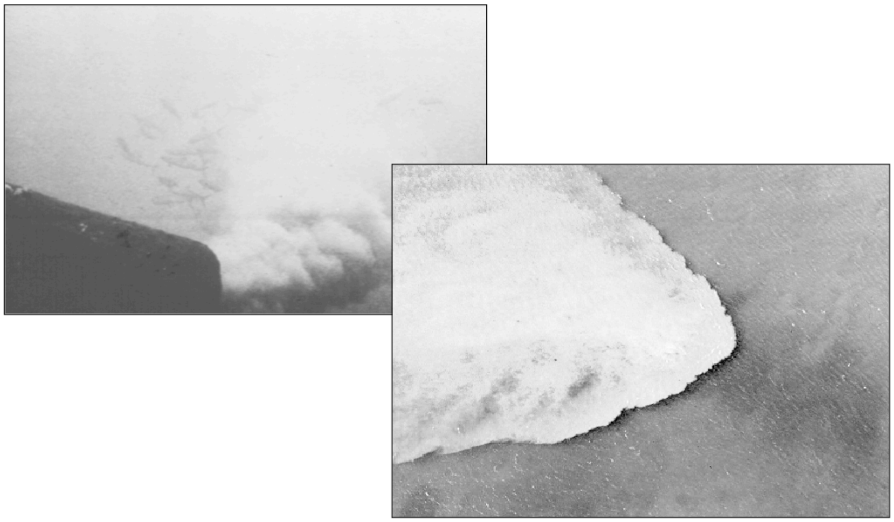
Example of Mixing Process



Sand Island Outfall: 62 MGD, a 60-inch diameter outfall pipe about 3,700 feet offshore and at a depth of 38 feet.

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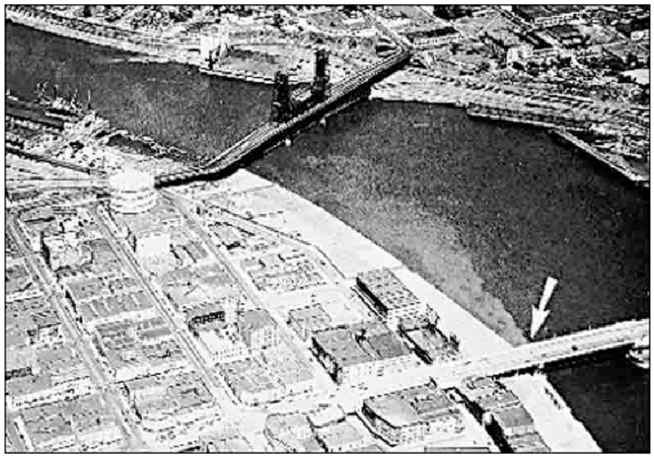
Example of Mixing Process



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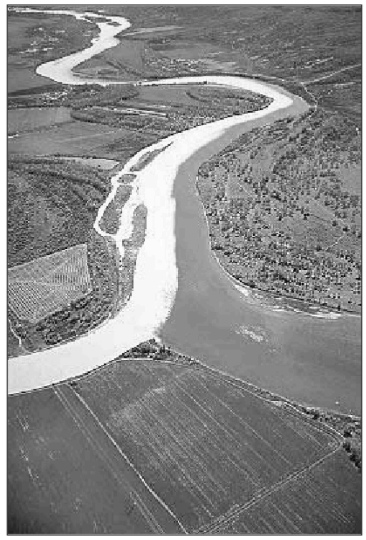

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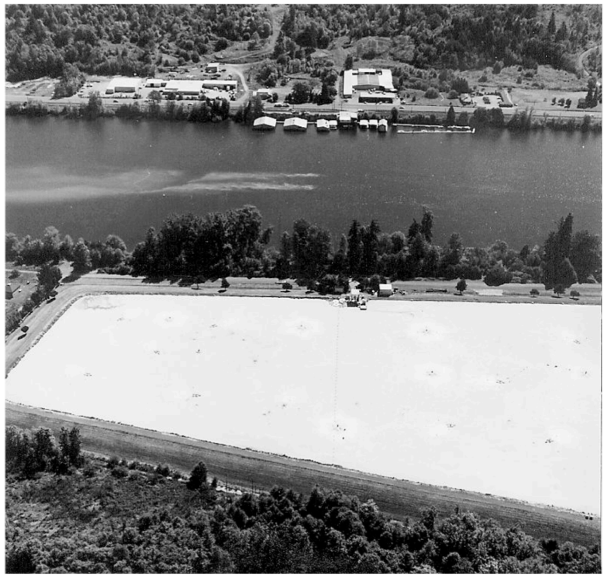

Example of Mixing Process

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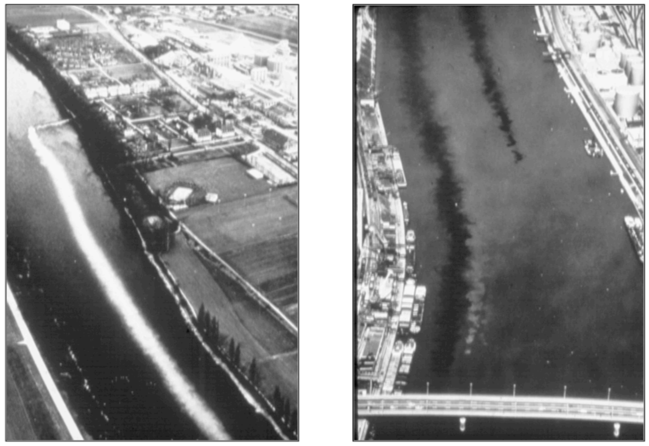

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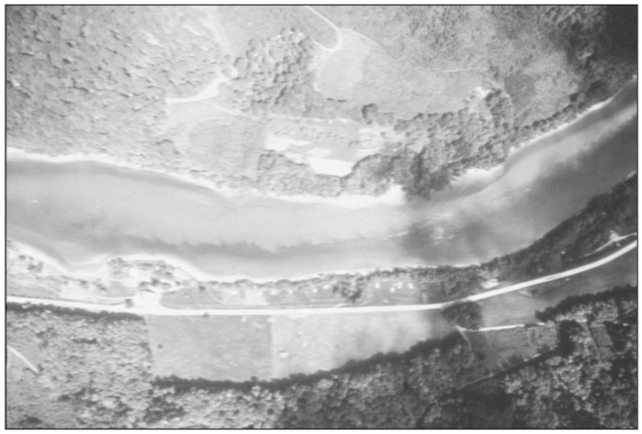

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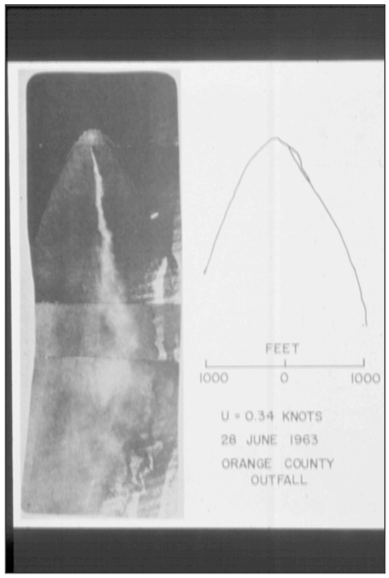

Example of Mixing Process

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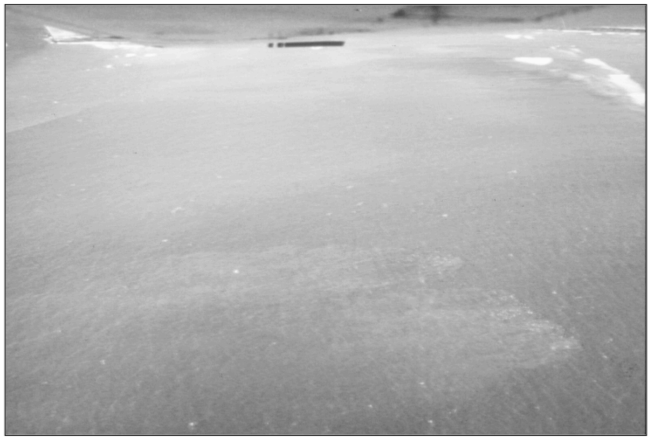

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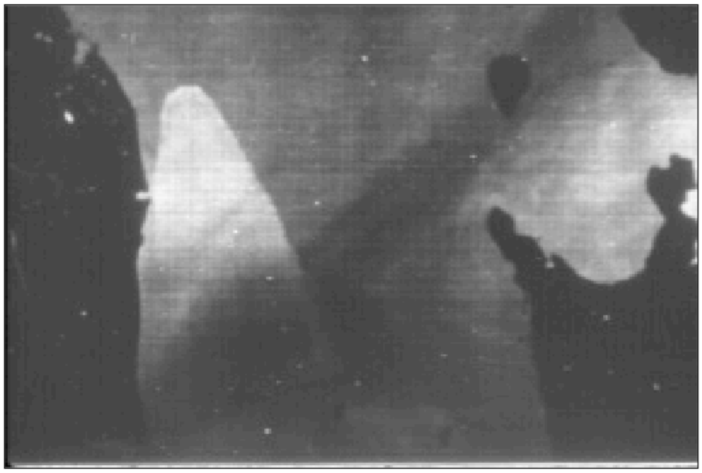

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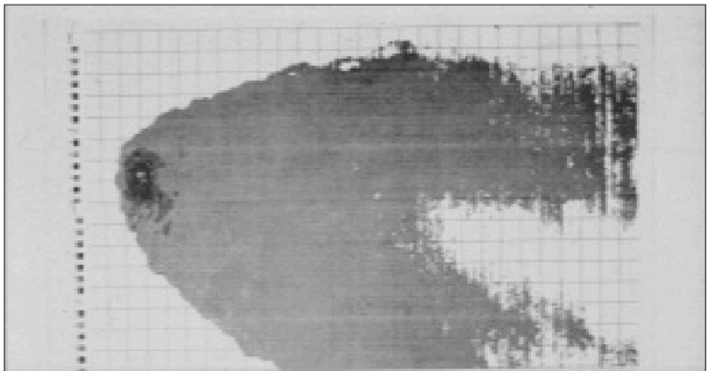


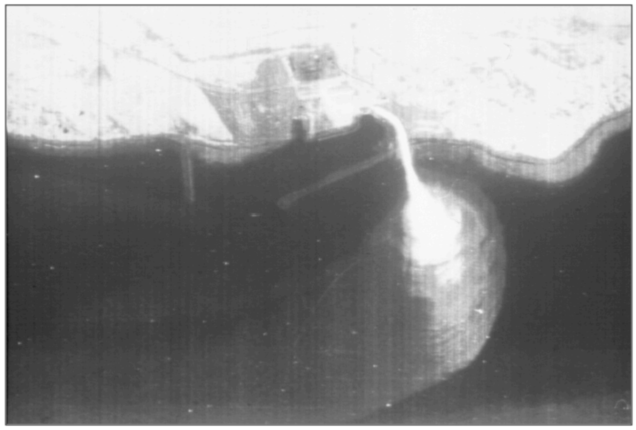
Figure 9.30 Thermal discharge ($Q = 21\ m^3/sec$) from a coastal power plant made visible with a scanning infrared radiometer. Vertical discharge is 5 m below the surface and the peak temperature difference is 11.1°C. There is a coastal current of 0.27 knot (0.14 m/sec) and grid spacing is 30.5 m (100 ft). Note bifurcation of the plume.

Example of Mixing Process

Example of Mixing Process

Shoreline Discharge Example

Example of Mixing Process



Example of Mixing Process

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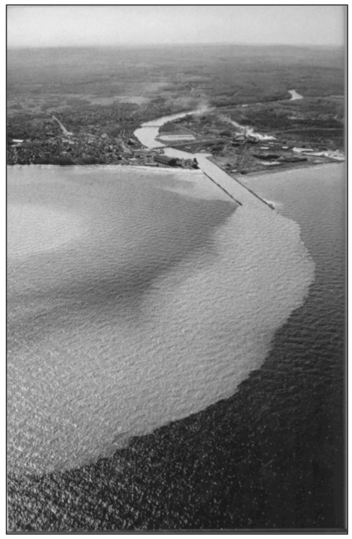

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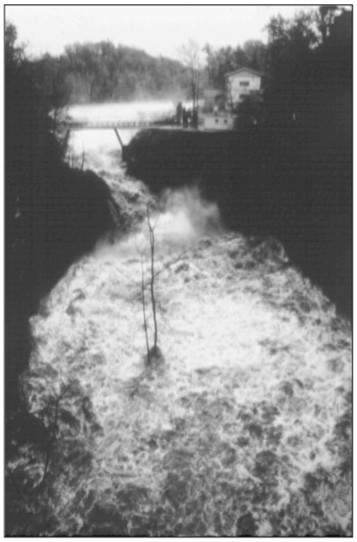

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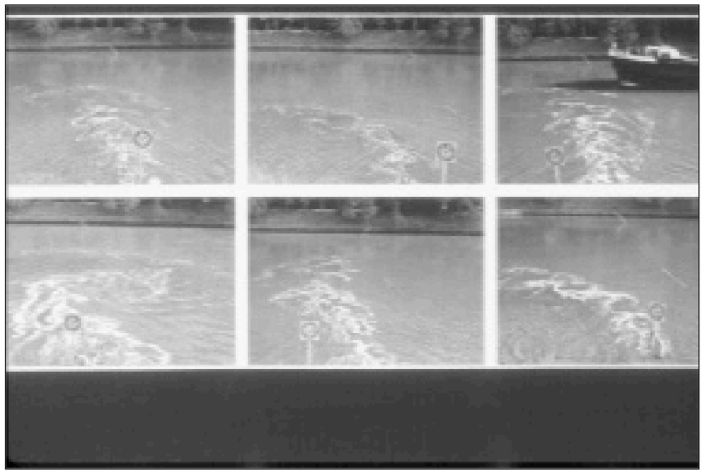
Example of Mixing Process



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Example of Mixing Process

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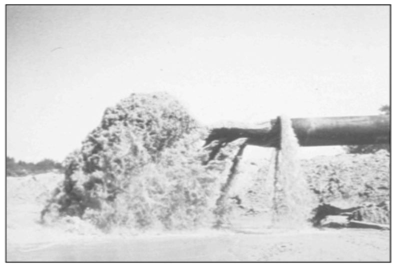
Dense Discharges



Produced Water & Drilling Muds

Produced Water, Drilling Muds and Cuttings discharged from offshore operations

Additional Examples of Mixing Processes

- http://www.cormix.info/picgal/index.php

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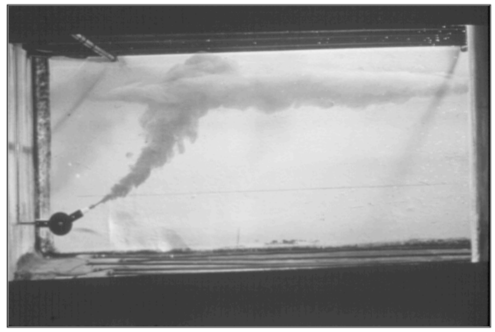
Near-field Mixing Processes

- Buoyant Jet Mixing
  - Momentum/Buoyancy
  - Crossflow effects
  - Density Stratification
- Boundary Interactions
  - Surface, bottom
  - Interface, terminal layers
  - Approach flow
  - Impingement flow
  - Near-field Instability
  - Dynamic Attachments
    - Wake
    - Coanda

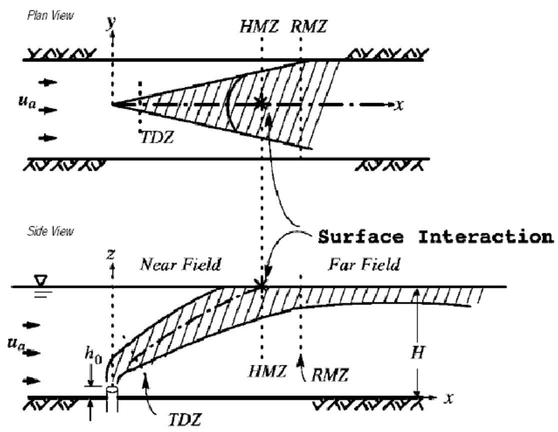


Far-field Mixing Processes

- Density Current / Buoyant Spreading
  - Stratified Flow
  - Boundary Interaction
- Passive Diffusion
  - Uniform/stratified ambient conditions

Location of Mixing Zones

- Toxic Dilution Zone (TDZ)
  - usually in near-field
- Regulatory Mixing Zone (RMZ)
  - near-field or far-field
- Hydrodynamic Mixing Zone (HMZ)
  - region <u>including</u> any boundary interactions (e.g., surface)



Note: HMZ is the surface; plume contacts left bank in far-field

Figure 2-1: *Near-field and Far-field of a Single Port, Positively Buoyant Discharge*

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Initial Near-field Mixing Processes

- Submerged buoyant jet mixing
  - Initial mixing caused by **turbulent shear**
  - Buoyant jet **entrains** ambient fluid and is **diluted**
  - **Width** of turbulent zone **increases** with **distance** away from source
  - Initially **"jet-like"** finally **"plume-like"**
- Boundary Interaction
- Surface/bottom buoyant jet mixing

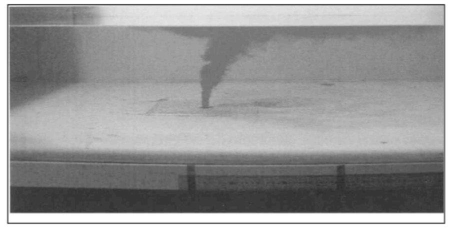

Photo: Torbin Larsen

Submerged Buoyant Jet Mixing in Stagnant Ambient

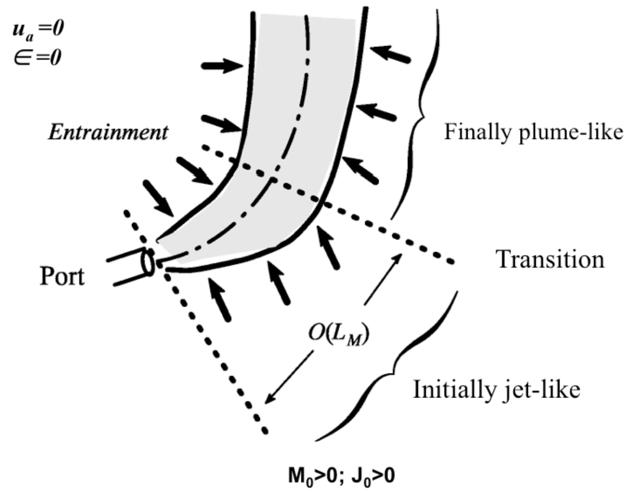

Figure 2-2: Buoyant Jet in Stagnant Uniform Environment

Pure Jet Mixing In Crossflow

- Figure 2-3 shows ***"pure jet"*** or ***"momentum jet"*** in crossflow
- Initially ***jet momentum*** controls mixing and trajectory
- Finally ***jet momentum and ambient crossflow*** control mixing and trajectory

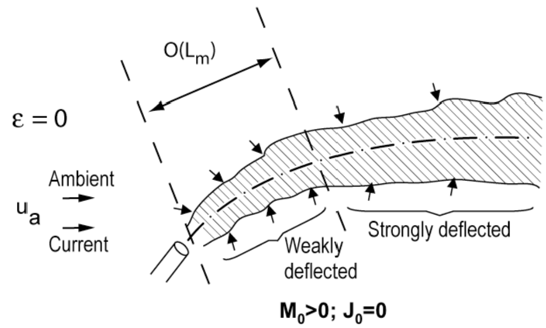

Figure 2-3: Pure Jet in Uniform Crossflow

Pure Plume in Crossflow

- Figure 2-4 shows "***pure plume***" or "***thermal***" in crossflow
- ***Initially*** plume buoyancy controls mixing and trajectory
- ***Finally*** plume buoyancy and ambient crossflow control mixing and trajectory

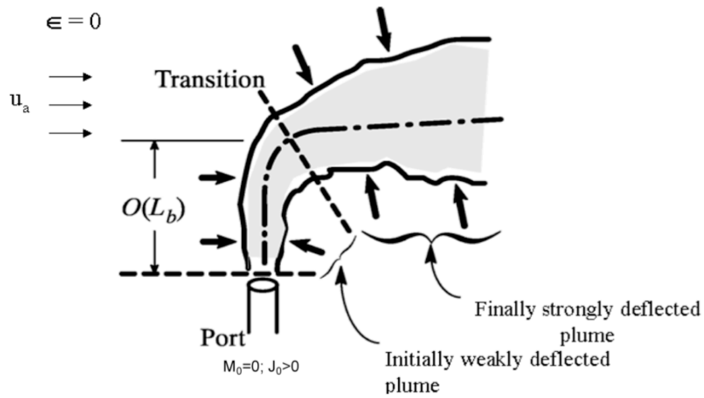

Figure 2-4: Pure (or thermal) Plume in Uniform Crossflow

Pure Jet in Stagnant Stratified Ambient

- Initially jet ***momentum*** controls mixing and trajectory
- Ambient ***density gradient*** traps jet at ***terminal level***
- Finally jet behaves as a ***density current***
- Shown in Figure 2-5

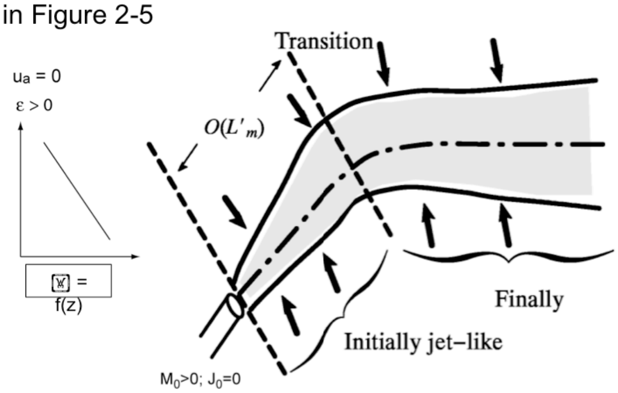

Figure 2-5: Pure Jet in Stagnant Stratified Ambient

Pure Plume in Stagnant Stratified Ambient

- Initially ***buoyancy*** controls mixing and trajectory
- Ambient ***density gradient*** traps plume at ***terminal level***
- Finally plume behaves as a ***density current***
- Shown in Figure 2-6

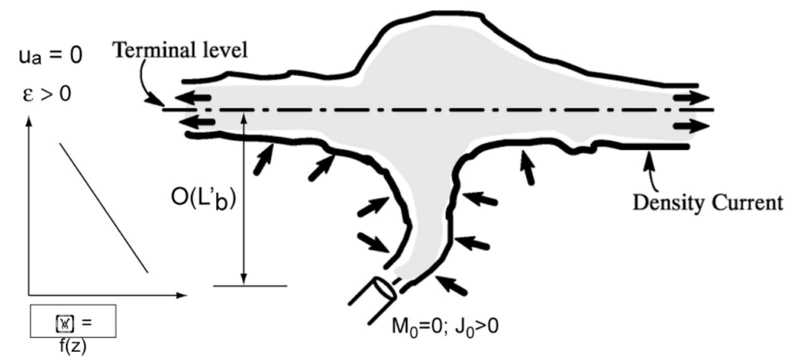

Figure 2-6: Pure Plume in Stagnant Stratified Ambient

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Jet Merging of Unidirectional Multiport Diffuser Forming Plane Buoyant Jet

- Initially jets behave ***independently***
- After merging a ***two dimensional plane*** or ***slot*** is formed
- ***Merged jet momentum*** may induce ***significant ambient current***
- Figure 2-7 shows individual jets merging

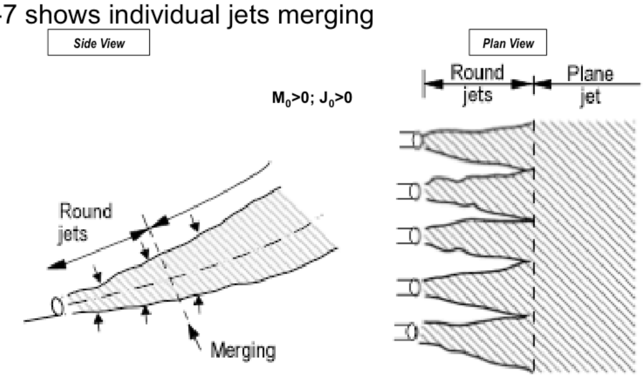
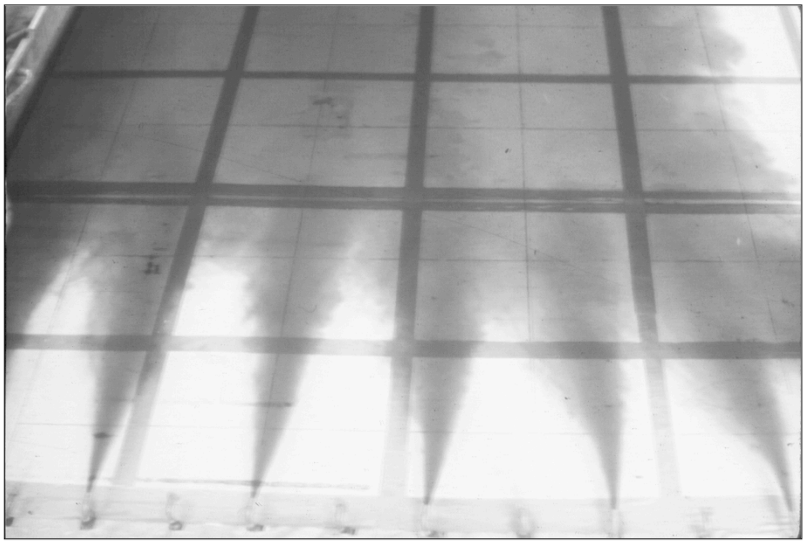


Figure 2-7: Jet Merging of Unidirectional Multiport Diffuser Forming Plane Buoyant Jet

Jet Merging of Unidirectional Multiport Diffuser Forming Plane Buoyant Jet



Jet Merging of Unidirectional Multiport Diffuser Forming Plane Buoyant Jet

Near-field Boundary Interactions and Stability

- Ambient water bodies ***always have vertical boundaries!***
  - E.g., Bottom, Surface, Pycnoclines
- Dynamics of boundary interaction depend on:
  - Buoyant jet characteristics
  - Ambient geometry
- ***Boundaries*** *provide* ***transition*** between ***near***- and ***far***-field mixing processes
- ***Stable discharge*** conditions
  - Strong buoyancy, weak momentum, deep water
  - Referred to as “deep water” conditions
  - Shown in Figures 2-8, 2-9
- ***Unstable discharge*** conditions
  - Weak buoyancy, strong momentum, shallow water
  - Referred to as “shallow water” conditions
  - Shown in Figures 2-10, 2-11

Stable ("Deep Water") Discharge Conditions

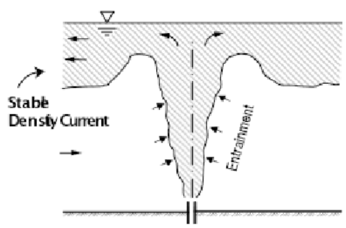


Figure 2-8: Deep Water, Strong Buoyancy, Vertical Stable Near-field

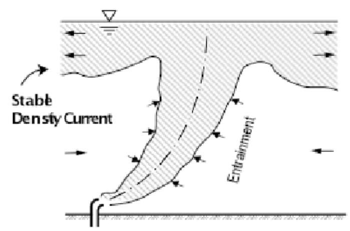


Figure 2-9: Deep Water, Strong Buoyancy, Near-horizontal Stable Near-field

$M_0>0$; $J_0>0$

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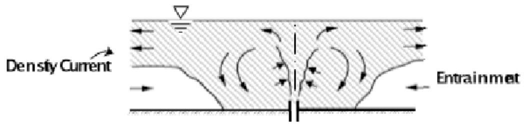
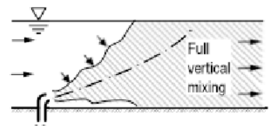
Unstable ("Shallow Water") Discharge Conditions



$M_0>0;\ J_0>>0$

Figure 2-10: Shallow Water, Low Buoyancy, Vertical: Unstable Near-field with Local Mixing Re-stratification



$M_0>>0;\ J_0 \approx 0$

Figure 2-11: Shallow Water, Low Buoyancy, Near-Horizontal: Unstable Near Field with Full Vertical Mixing

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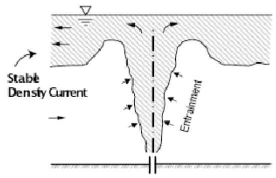
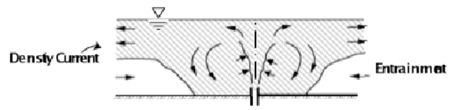
Stable vs. Unstable Discharge Conditions





Stable

Unstable

Experiments and Photos: Philip J.W. Roberts, Georgia Institute of Technology

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CORMIX Surface/Boundary Interaction Processes

- Important examples are given below for a ***single round buoyant jet***
- Figure 2-12 shows ***buoyant jet*** well ***deflected*** by ambient current at ***surface contact***
- Transition to ***far-field*** mixing occurs as ***smooth transaction*** with ***little*** additional mixing

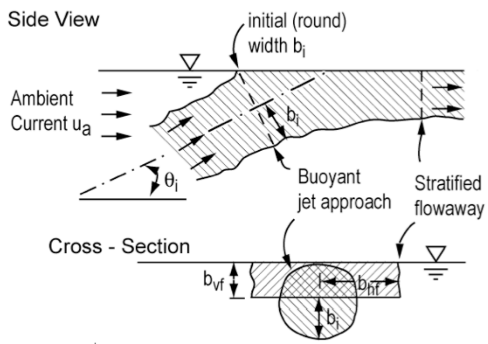

Figure 2-12: Gradual Surface Approach (near horizontal)

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Boundary Interaction – Stable w/ Intrusion

- If plume approaches **boundary (near) normally, rapid flow results** in all directions after contact
- If plume **buoyancy is strong** and **momentum relatively weak,** a **stable layer** will form at the surface
- In the presence of a **crossflow,** will give rise to an **upstream buoyant intrusion**

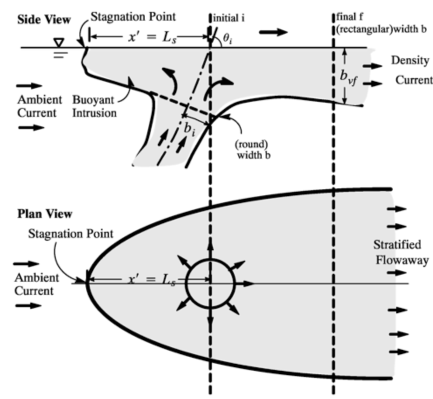

Figure 2-13: Surface Impingement with Buoyant Upstream Spreading

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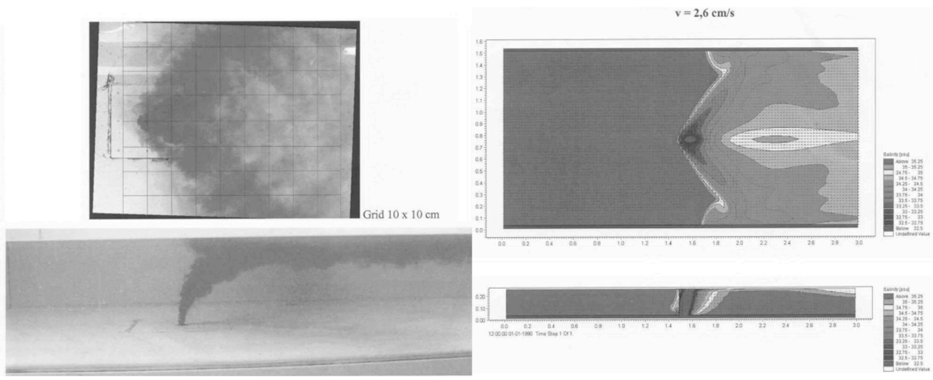
Boundary Interaction – Stable w/ Intrusion



Boundary Interaction- Instability

- If plume ***buoyancy is relatively weak*** and ***momentum relatively strong,*** leads to ***unstable recirculation*** in the discharge vicinity

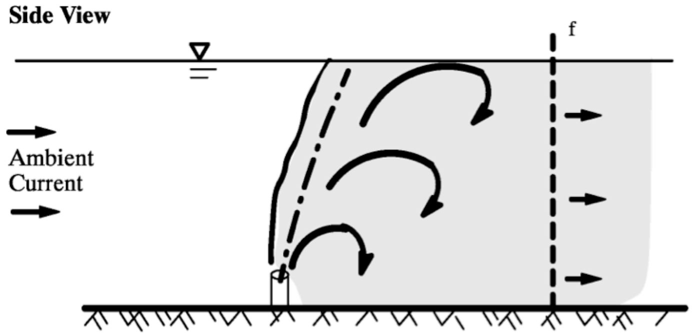
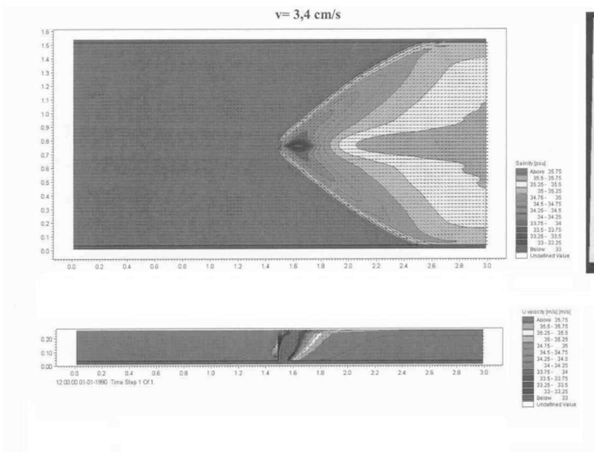
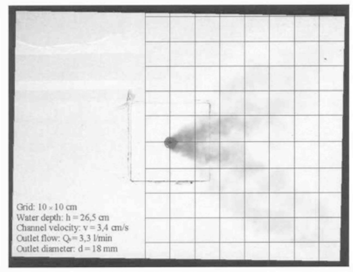
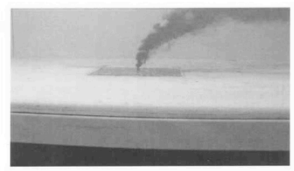


Figure 2-14: Surface Impingement with Full Vertical Mixing in Shallow Water

Boundary Interaction- Instability







Boundary Interaction- Unstable w/Intrusion

- If plume both ***buoyancy and momentum*** are relatively ***strong***
  - ***Unstable recirculation*** occurs in the discharge vicinity
  - ***Upstream density current*** will form
  - ***Re-stratification*** due to ***buoyancy*** will re-stratify plume

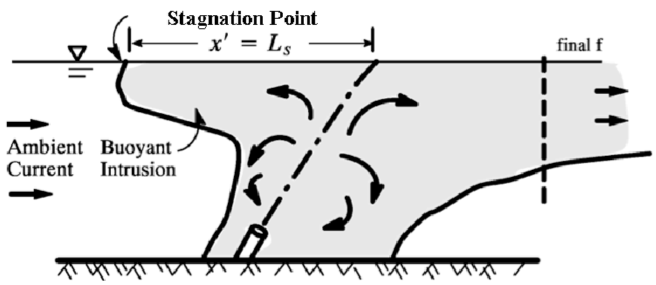


Figure 2-15: Surface Impingement with Local Vertical Mixing, Buoyant Upstream Spreading, and Re-stratification

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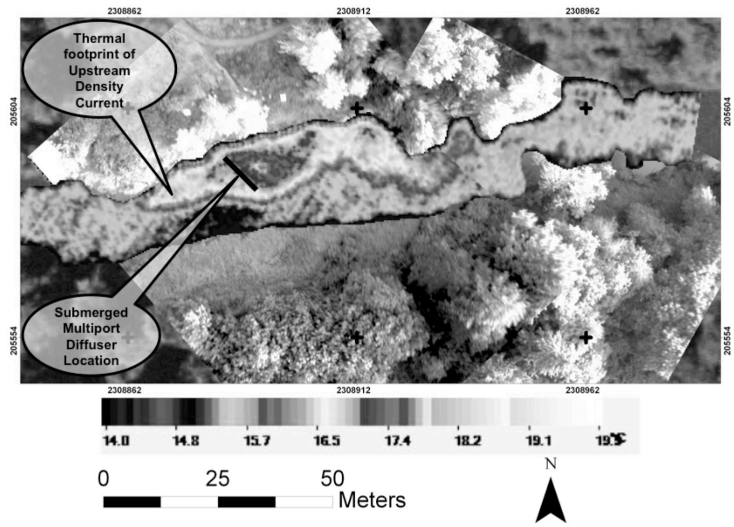
Field Example - Upstream Density from a WWTP



Infrared Aerial Image of Upstream Density Current - (MixZon's Aerial Remote Sensing Platform)

Dynamic Near-field Bottom Attachments

- **Bottom attachments** are of concern because of **benthic impacts**
- Outfall design may cause/fix **near-field** plume **attachments**
- **Two types** of dynamic bottom attachment possible
  - **Wake attachment**
    - Caused by **disruption** of **ambient flow** caused by port in crossflow
  - **Coanda attachment**
    - Caused by **low pressure** of effects jet located near the water bottom
- Similar near-field **surface attachments** for near surface discharges

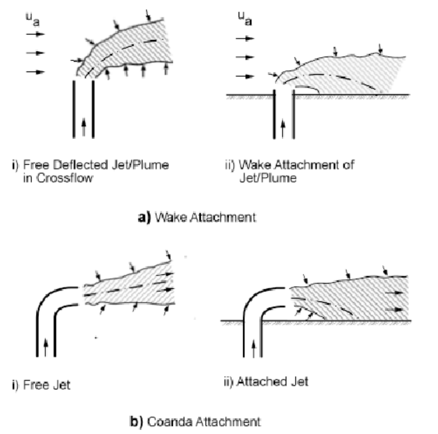


Figure 2-16: Flow patterns for single port discharges (i) away from and (ii) close to bottom surface

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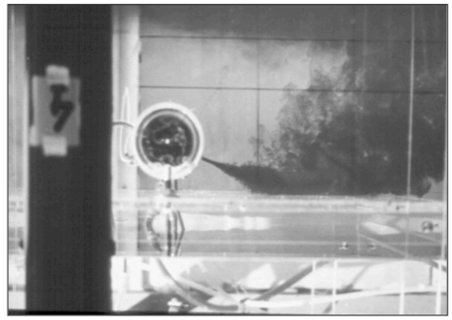
Near-field Dynamic Attachments

Unattached Flow



Coanda Attachment

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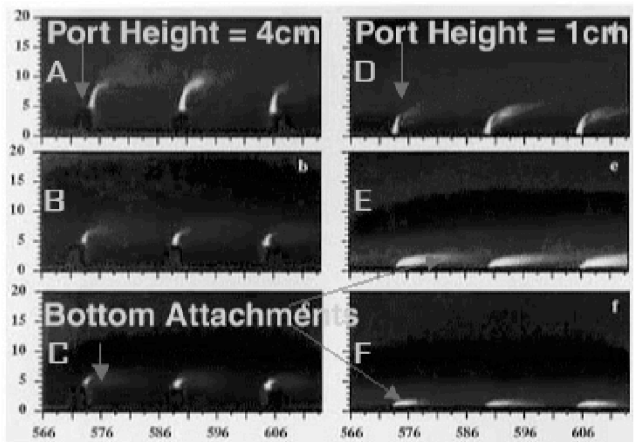
Example: Near Field Wake Attachment



The false-color, laser-induced fluorescence images illustrates boundary interaction behavior for a multiport diffuser in crossflow. U_a increases from the top series to the bottom, causing plume wake attachment (C, E, F).
The greater discharge port height on the left (A, B, C) resists bottom attachment as crossflow velocity increases.
Wake attachment, indicated by a CORMIX (..) A2 flow class, can have undesirable and avoidable benthic ecological impacts. (Photo: S. Monismith)

Crossflow velocity (left to right) is increased from

Diffuser Induced Intermediate Field Effects

- Some diffuser types ***induce ambient flows*** because of ***discharge momentum***
- Effects occur well ***beyond*** the initial ***near–field*** region
- Associated with ***unstable discharges*** in shallow water when discharge ***buoyancy is weak***
- For ***unidirectional*** & ***staged*** diffusers strong ***vertically mixed*** currents occur with ***lateral entrainment***
- May ***extend*** over large distances before ***re-stratification*** or ***momentum dissipation***

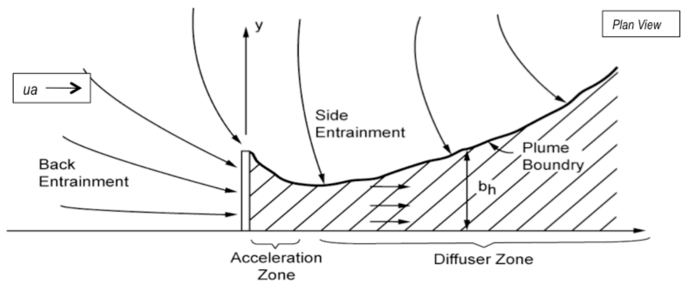
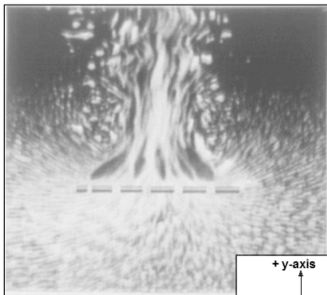
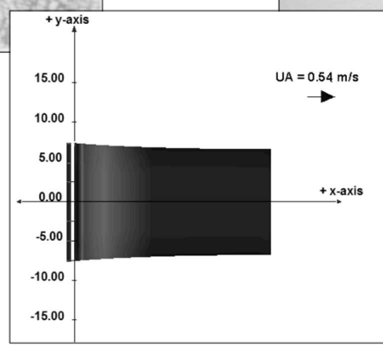


Figure 2-17: Flow Field Induced by Unidirectional Diffuser: Structure of Diffuser Plume (half-plane with symmetry line)

Example: Diffuser Induced Acceleration





Surface Buoyant Discharge Mixing

- Have ***similarities*** to corresponding ***submerged jet***
- Initially mixing is controlled by ***initial momentum*** and ***buoyancy***
- Vertical ***entrainment*** becomes ***limited*** after a short distance, ***lateral spreading*** becomes large
- In ***stagnant conditions,*** thin ***surface layer*** forms
  - ***Transient spreading*** motions occur for ***stagnant ambient***
  - Shown if Figure 2-18a

Surface Buoyant Discharge Mixing

- If ***crossflow*** is present and initial ***lateral momentum*** is **strong, *no shoreline*** contact will occur
  - Shown in Figure 2-18b
- If ***crossflow*** is present and ***initial lateral momentum*** is **weak, *shoreline contact*** can occur
  - Shown in Figure 2-18c
- If ***crossflow*** is present and ***initial lateral momentum*** is **weak** and ***buoyancy*** is **strong, *shoreline contact*** and ***upstream buoyant intrusion*** can occur
  - Shown in Figure 2-18d

Surface Buoyant Jet Mixing

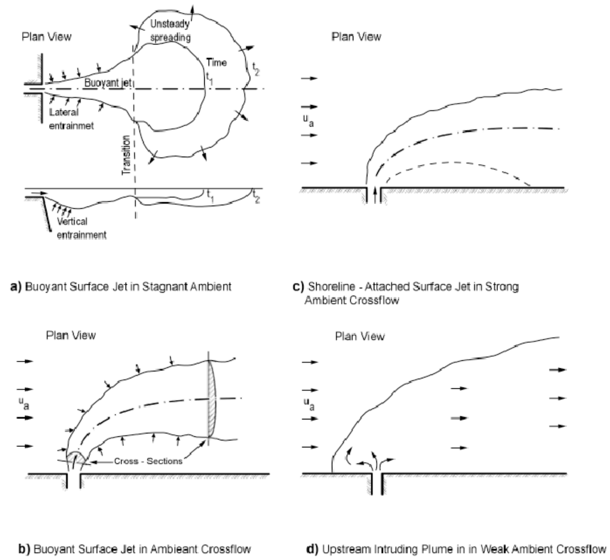


Figure 2-18: Typical Buoyant Surface Jet Mixing Flow Patterns

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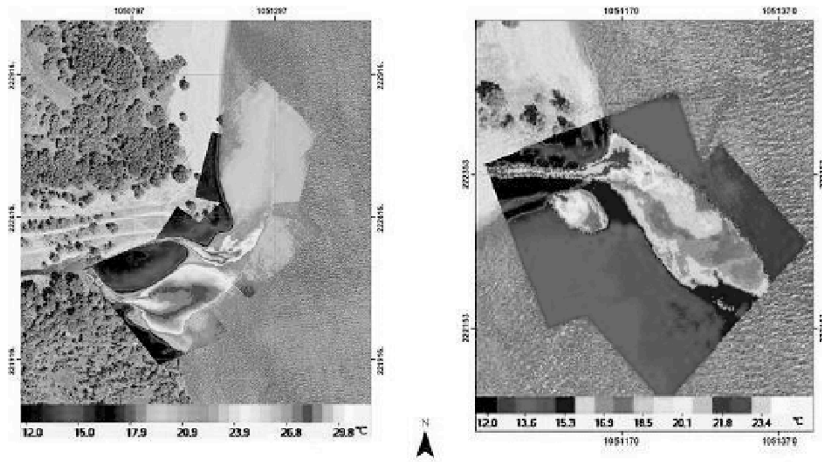
Field Example – Surface Buoyant Jet Mixing



Geo-rectified, aerial thermal IR image of a cooling water discharge Mixing Zone into the Columbia River, OR. Images show thermal plume mixing before (Left) and after (Right) outfall rehabilitation and tidal influence on the effluent plume.

Far-field Mixing: Density Current/Buoyant Spreading

- ***Far-field*** mixing processes occur after ***boundary interaction***
- If ***buoyancy*** is present, ***density current/buoyant spreading*** will occur
  - Buoyancy ***delays*** the transition to far-field ***passive diffusion***
- ***Buoyant spreading*** includes
  - **Surface** spreading
  - **Bottom** spreading
  - **Pycnocline** spreading (ambient density jump)
  - **Terminal level** spreading
- ***Mixing*** occurs at the ***"head region",*** much like a ***density current*** (Figure 2-19)
- ***Mixing*** is relatively ***small*** in ***buoyant spreading***

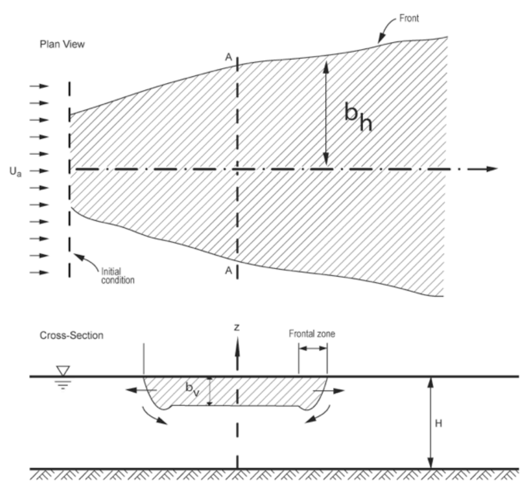


Figure 2-19: Typical Buoyant Spreading/Density Mixing Flow Patterns

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Far-field Mixing: Density Current/Buoyant Spreading

- **Special Case - *Heated discharges***
  - ***Density difference decreases*** due to mixing and heat transfer
  - ***Heat transfer*** is dependent on ***wind velocity***
  - ***Buoyant spreading*** module may collapse into a ***thin layer***
  - Plume may interact with ***lateral boundary*** in this phase
  - Eventually, the ***buoyancy*** force ***dissipates*** and the transition to ***passive mixing*** occurs
- **Special Case – *Suspended Sediment discharges***
  - ***Density difference decreases*** due to mixing and particle settling
  - Density current goes down gradient while advected by crossflow
  - Bottom slope is needed for far-field behavior

Far-field Mixing: Passive Diffusion

- Eventually existing ***ambient turbulence*** will ***control mixing***
- Diffusing plume grows ***laterally*** and ***vertically*** until ***interaction*** with ***bottom/surface*** and/or ***banks***
- Intensity of ***diffusion*** depends on production of ***turbulent shear*** in ambient ***velocity profile***
  - Specified by Darcy ***f***
  - Influenced by ***Channel Roughness***
  - Adjusted in CORMIX by ***Channel Appearance***
    - Straight, Slight Meander, Highly Irregular
  - Enhanced by Wind Velocity

Far-field Mixing: Passive Diffusion

- For **bounded channels**
  - Turbulent ***diffusivities*** are ***constants*** described by length scales
  - ***Vertical*** and ***horizontal*** diffusivities related to ***channel depth*** and ***width,*** respectively
  - Diffusivities are also effect by ***channel meandering***
- For **unbounded channels**
  - Plume ***growth*** proportional to ***plume size***
  - Diffusivity described by ***"4/3" power law***
- Figure 2-20 illustrates a ***passive diffusion process*** for a s***urface plume*** in a ***bounded channel***
- Possible Bottom Interaction

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Far-field Mixing: Passive Diffusion

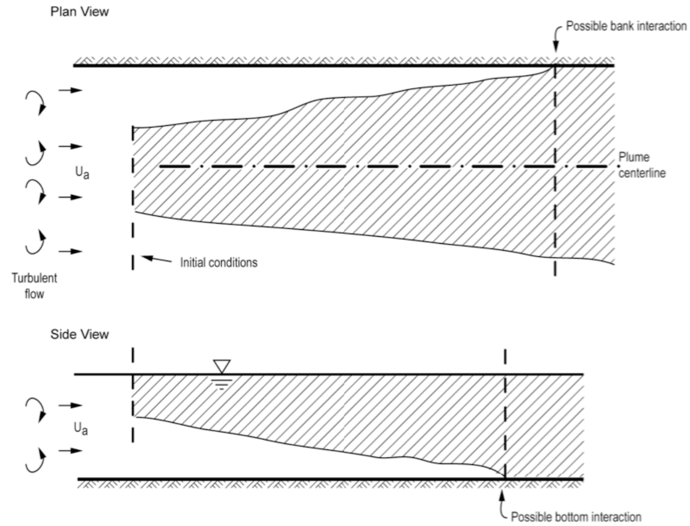

Figure 2-20: Example of Ambient Passive Diffusion Flow Patterns

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Example of Mixing Process

Part 2 - Section Summary

- Mixing conditions
- Environmental mixing processes
- Physical processes which control mixing
- Near-field mixing
- Boundary interaction processes
  - Discharge stability
- Far-field mixing
  - Density currents
  - Passive diffusion
- Q & A