The importance of mixing and isolation time for desalination brine discharge

Ben R. Hodges

***Abstract*—**Hypersaline gravity plumes, such as resulting from desalination discharge into the ocean, an estuary, or coastal embayment, may cause development of hypoxic (low dissolved oxygen, DO) or anoxic (zero DO) regions that are detrimental to the environment. Previously, desalination discharge mixing has been classified by near and far-field zones, with most research focusing on the former. Herein, we propose a new classification including inertial, transitional, spreading, and frontal far-field regions with different mixing characteristics. We show that entrainment dominates the inertial far-field region where hypoxia is relatively unlikely. In the spreading far-field region, entrainment into the plume is minimal and ambient turbulence tends to erode the plume without changing its salinity anomaly or DO content. As a result, if ambient turbulence is too low, thin layers will develop out at a distance from the source and are likely to become rapidly hypoxic. Using field data we show that a newly-defined non-dimensional "isolation time" provides an improved approach to evaluate the relationship between stratification and hypoxia.

***Keywords*—**desalination, hypoxia, stratification, turbulence.

1. INTRODUCTION

DESALINATION brine discharges have both direct and indirect environmental impacts. The high salinities of the discharge water have direct impacts where benthic aquatic organisms have limited salinity tolerance. If chemicals from the desalination process are included in the brine discharge, these may also have direct impacts on marine life. A key *indirect* impact, and the principal focus of this paper, is the development of hypoxia (low dissolved oxygen levels) in the discharge plume when insufficient mixing energy is available. This impact is indirect since it results from the interaction of the discharge with the environment, rather than from low dissolved oxygen (DO) in the discharge itself. The principal cause of hypoxia in a brine discharge plume is the reduced rate of DO resupply caused by stratification in combination with the environmental DO demands.

Desalination plants produce brine effluent that is on the order of twice the salinity of the source water. Near-field dilution at its discharge into an estuary, bay or ocean is generally no better than 10:1, which leaves a local salinity anomaly of three to five parts per thousand (ppt) greater than the receiving water (assuming source and receiving water have similar salinities). The diluted brine is typically 10% to 15% heavier than ambient water, creating a dense plume below the ambient water near the brine discharge site. Many coastal desalination discharges have natural mixing energy that can dissipate the plume fairly rapidly [1]; however, as desalination plants become more common, locations with sufficient mixing energy may be unavailable.

In studying the thin-layer gravity plumes in an arid region subject to natural evaporative development of hypersaline water (Corpus Christi Bay, Texas, USA) [2,3] we have developed an approach to evaluating hypoxia development in a hypersaline plume [4]. By examining mixing rates from various sources and the evolution of the plume we can understand the time scales over which hypoxia develops. A key insight is that these processes are difficult to correctly represent in existing three-dimensional (3D) hydrodynamic models that are used to model the far-field fate of desalination brine plumes. Model error in near-boundary processes tend to show over-prediction of plume mixing, providing artificially high DO resupply rates and artificially weakening the plume [5,6]. Because numerical diffusion is a cumulative one-way bias in any stable model [7], accuracy must degrade over the plume length. Analyses using mixing characteristics and isolation times as presented herein may eventually prove practical engineering tools for understanding far-field consequences of a brine plume. This research is still in its early stages, so in this paper we present the basic outlines of the ideas and process scaling.

2. BRINE PLUME ZONES

2.1 Overview

Past practice has been to separate desalination plume analysis into near-field mixing and far-field plume propagation. The near-field is dominated by non-hydrostatic behaviors and is generally analyzed by integral models [8,9,10,11]. The far-field plume may be modeled as vertically well-mixed by a 2D model if ambient mixing is considered sufficient [12,13]. However, modeling a dense gravity current underflow requires a 3D hydrostatic model [14,15,16], with the presumption that the model adequately represents the interaction of bottom topography, the buoyancy driven gravity plume, and mixing with the ambient.

The simplistic near/far-field concept neglects changes in the plume behavior in different areas of the far-field that affect hypoxia development. In Fig 1, showing the steady-state condition for a typical desalination brine plume, we can readily separate the far-field into inertial, transitional, spreading, and frontal zones. Each of the zones has different mixing characteristics and has different impacts on the development of hypoxia.

Manuscript received December 31, 2009.

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Funding for this project was provided by the Center for Research in Water Resources at the University of Texas at Austin, the Texas Advanced Technology Program (003658-0162 2003), the Texas Water Development Board (2005-001-059), and the U.S. National Science Foundation (CBET 0610034). In-kind support for the field study was provided by the Texas Water Development Board with support from the U.S. Army Corps of Engineers (Texas Water Allocation Assessment grant 2001-999-015).

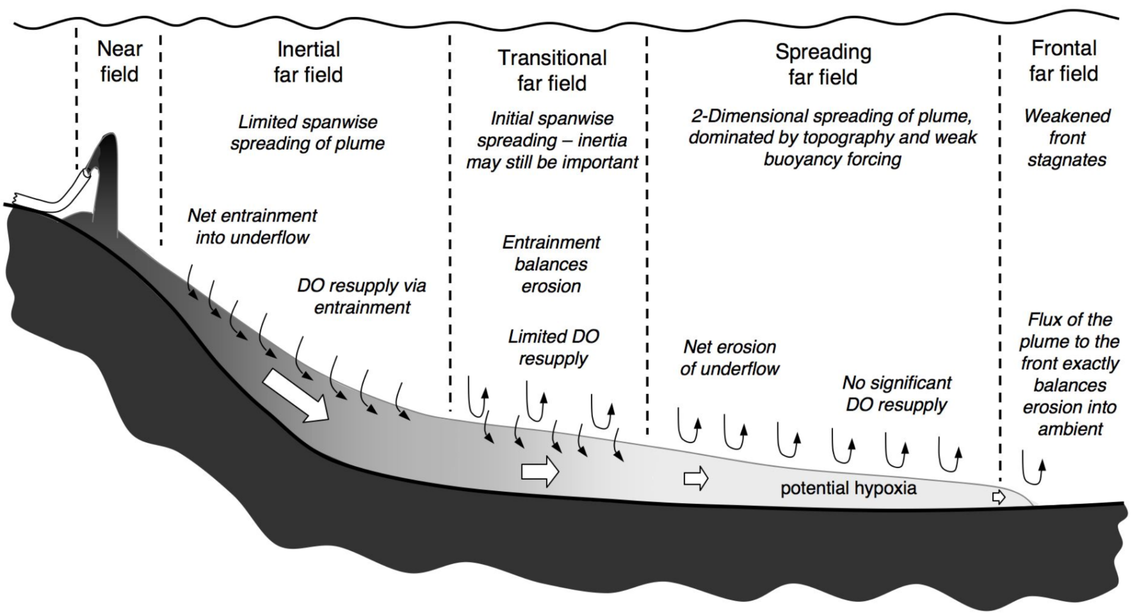

Fig 1. Conceptual picture of near and far-field mixing zones for a desalination brine plume where ambient turbulence is insufficient for full mixing through the water column.

2.2 Mixing Processes

We are interested in two mixing processes: entrainment of ambient water into the plume, and entrainment of plume into the overlying ambient water. Although both of these are technically forms of entrainment, in focusing on the plume we will use "entrainment" for mixing ambient water into the plume, thereby increasing the plume's thickness, reducing its salinity anomaly and resupplying DO. In contrast, turbulence in the overlying ambient water (e.g. velocity shear due to currents, wind or wave-driven turbulence) tends to erode the plume by entraining plume water into the ambient, thereby reducing the plume thickness without significantly altering its salinity anomaly or providing new DO. This latter process we will call "erosion".

2.3 Inertial Far-Field

Along steeply sloping bottoms, inertia plays a dominant role and classic gravity plume theory can be used to predict far-field effects in this zone – i.e. how the turbulence within the plume itself leads to further entrainment and dilution, [17,18,19]. For an inertial far-field, the erosion will be weaker than the entrainment. We characterize the vertical entrainment flux into the plume by a velocity W_E, and the vertical erosive flux into the ambient by W_A, so that the inertial far-field is characterized by

$$W_E > W_A \quad (1)$$

Bo Pedersen [20] showed that for a variety of conditions, a reasonable approximation of entrainment along a bottom slope of $\sin\psi$ can be obtained by

$$W_E \approx 0.072\, U \sin\psi \quad (2)$$

where U is the underflow characteristic velocity. A steady-state gravity plume propagates at some Froude number $F = U(g'H)^{-1/2}$ where H is the plume thickness and g' is the reduced gravity, which in terms of the ambient density and the density anomaly is $g' = g\Delta\rho/\rho_A$. It follows that

$$W_E \approx 0.072\, F\sqrt{g'H}\, \sin\psi \quad (3)$$

Characterizing the vertical erosive velocity (W_A) is more difficult as it depends upon the ambient turbulence. As long as plume thickness is small relative to water depth, the plume has limited effect on the overlying water hydrodynamics and 3D models may be used to estimate W_A. Alternatively, we have shown [4] scaling may be used to predict plume erosion due to wind mixing in shallow water

$$W_{A(\mathrm{wind})} \approx -C\left(\frac{\rho_{air}}{\rho_A}\right)^{3/2} \frac{U^3_{wind}}{g' D_A} \quad (4)$$

where D_A is the depth of the ambient water. We have not developed scaling for wave or ambient current-driven turbulence, so the utility of the approach is presently limited.

Further characterizing this region, the spanwise spreading of the plume (velocity V) is smaller than the plume propagation down-slope, so

$$V < U \quad (5)$$

In the inertial far-field plume is moving relatively fast, is still close to the original source with high DO levels, and is receiving additional DO via entrainment from the ambient. Thus, this region is unlikely to see development of hypoxia. However, confirmation for any particular plume requires knowledge of DO demands rates relative to the fluxes (see Sections 3 and 6 below).

2.4 Transitional Far-Field

As either the plume density anomaly weakens (due to entrainment), the bottom slope lessens or the ambient turbulence increases, the plume will reach a transitional regime where the inertial forcing will be less important and bottom-drag plays an increasing role [21]. A balance between entrainment and erosion may be reached:

$$W_E \sim W_A \quad (6)$$

For a plume that is restricted from spreading in the spanwise direction, the plume height will remain relatively constant. However, if the bottom flattens out (as commonly the case), the plume will tend to spread horizontally across the bottom, which reduces both H and U.

From eq. (3), we see that reduction in g' and $\sin\psi$ both will decrease W_E, so DO replenishment will be reduced in the transitional far-field. If natural DO demands are high, hypoxia may develop in this area, but is relatively unlikely.

2.5 Spreading Far-Field

Beyond the transitional far-field, the reduction of g' and/or $\sin\psi$ leads to erosion dominating entrainment, such that

$$W_E < W_A \tag{7}$$

In this region, the plume slows, spreads, and gets thinner. The erosion of the plume does not significantly mix ambient water or DO into the plume, so there is a significant risk for hypoxia. As the plume becomes thinner around its outer edges, the risk of hypoxia becomes much greater. The thinness of the plume in this area makes it difficult to correctly capture in a 3D hydrodynamic model [6]. Thus, the very area where hypoxia is the greatest risk is the area that is most difficult to model.

2.6 Frontal Far-Field

The front of the far-field occurs where the flux of the plume is equal to the erosion rate from the ambient, so that all the remaining plume water is mixed into the ambient.

$$U \sim W_A \tag{8}$$

or

$$W_A \sim F\sqrt{g' H} \tag{9}$$

The frontal far-field will oscillate across the landscape as a function of the ambient flow field. Unfortunately, our understanding of the quasi-steady front conditions of continuous discharges are presently rudimentary. The majority of gravity-plume frontal studies have been associated with impulse flows with a propagating front [22,23,24] that may not be directly applicable to a continuous discharge.

3. DO Dynamics

Dissolved oxygen (DO) is both consumed and produced in biogeochemical cycles driven by aquatic organisms in the water column and sediment. The complexities of these biogeochemical cycles depend upon the species composition of both flora and fauna, as well as nutrient availability, sediment chemistry, and available sunlight. The daily DO cycle for micro-organisms (e.g. phytoplankton) includes production of DO during daylight hours and respiration (DO consumption) during the night. Decomposition of organic materials in the sediments provides additional demands for DO, which is converted into CO_2 by bacteria. This simple thumbnail sketch does not do justice to the complexities of the actual processes. Sophisticated DO and ecosystem process models have been created, but their use requires extensive expertise for application. However, we believe that if we can obtain sufficient data and understanding with site-based field studies and simpler mass-balance models, such full ecosystem models may not be necessary.

In many cases the characteristic scales of the DO cycle can be estimated from field data [25,26]. For the present work, we are interested in the net DO daily demand in both the water column and the sediments. The net rate at which oxygen is added to the water column (production – respiration) is known as the Net Ecosystem Metabolism (NEM). The DO demand by the sediments is known as the Sediment Oxygen Demand (SOD).

The SOD becomes the critical parameter as the plume gets thinner in the spreading far-field region of Fig. 1. With entrainment to the plume almost non-existent, the thinning layer requires all the SOD to be supplied by a smaller and smaller volume of water. The relationship between the DO demands and the thinness of the layer allows hypoxia to be developed very rapidly, and maintained over a long time despite the continual influx of new water in the plume.

4. Field Study

A field study was conducted during the summer of 2005 to document a hypersaline plume that exits from Oso Bay into Corpus Christi Bay, Texas (USA). The former is a small shallow bay (< 0.5 m deep, 2 km across, 10 km length) with salinities typically greater than 45 ppt (parts per thousand) during the summer. The latter is a larger bay, approximately circular and 20 km in diameter with summer salinities near 37 ppt. Corpus Christi Bay has flat bottom with a relatively uniform depth of 3.5 to 4.0 m across most of the bay. The field study was conducted over a 48-hour period by sampling temperature (T), depth (D), conductivity (C), and dissolved oxygen (DO). Salinities (S) were computed from conductivity, temperature and depth within the profiling instrument (Eureka Environmental Engineering Manta™ Profiler) [2,3,4].

The hypersaline plume developed at the connection between Oso Bay and Corpus Christi Bay results from naturally–developed hypersalinity in an adjacent bay that is pumped into Oso Bay by a power plant. This outflow has scales similar to those expected for the far field salt load of a 3.8 x 10^5 m^3/d desalination plant, so it provides a useful study for effects of large brine plumes in a shallow bay.

Fig. 2 shows profiles of temperature, salinity and DO across a typical afternoon transect of the bay (1500 – 1800 hours). During the afternoon, the outflow from Oso Bay is warm (34 C), hypersaline (55 ppt) and high in DO (9 mg/l) due to extreme productivity in Oso Bay. As the gravity plume moves down-slope within about 1200 m of Oso Bay the salinity, and temperature are reduced by entrainment. During the daytime, productivity in the water column keeps DO in this region relatively constant. Out beyond 1200 m, the temperature and DO in the underflow are quite different, which can be better understood by examining a typical early morning (0300 – 0600 hours) transect in Fig. 3.

During the night and early morning, the water in Oso Bay cools more rapidly than Corpus Christi Bay, resulting in a cold salty underflow that can be seen up to 1500 m offshore in Fig. 3. Beyond 1500 m in Fig. 3 is a pocket of warmer salty water – remnants of the previous afternoon's underflow. Similarly, in Fig. 2 the cool salty water seen out beyond 1200 m is from the prior night's underflow.

In Figs. 2 and 3., DO is low beyond 1800m throughout the study. Data from the outermost sampling site collected near the bottom is shown in Fig. 4. Note that the low DO in this region occurs whether or not the source water (Oso Bay) had high (~ 9 mg/l) or moderate (~ 4 mg/l) DO levels.

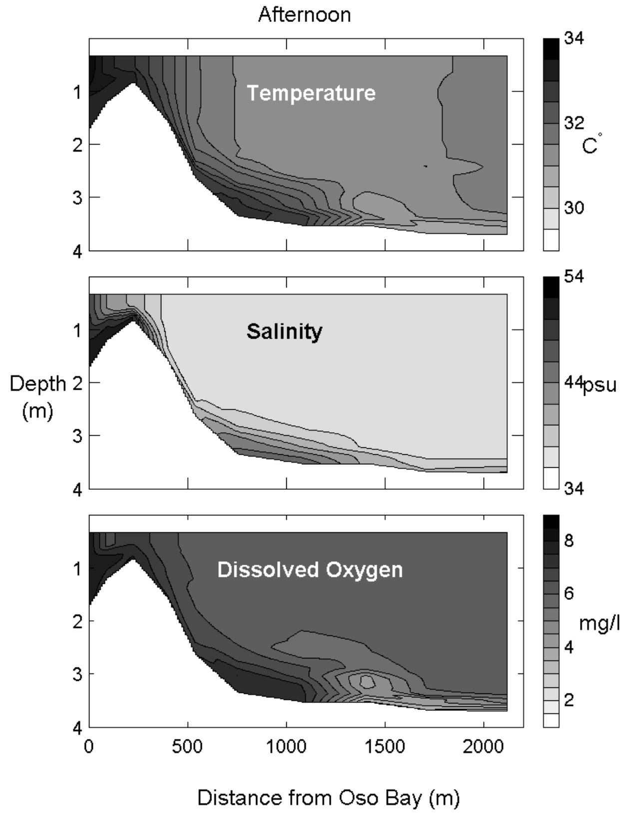

Fig. 2. Contours of transect data during afternoon hours. Low DO is seen out at the furthest point from the Oso Bay inflow. Underflow near to Oso Bay is warm, highly saline and also high in DO. Note that subsequent surveys showed there is a channel narrow approximately 1.8 ~ 2 m deep that cuts through the apparent shoal at about 200 m. Data in this channel was not collected during the field study, but is expected to be contiguous with the contours shown.

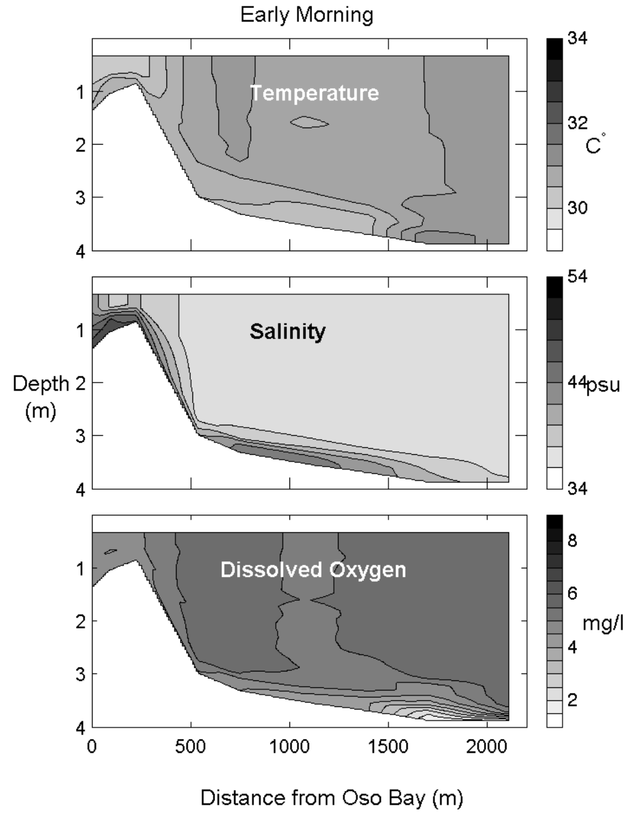

Fig. 3. Contours of transect data during early morning hours. Low DO is seen out at the furthest point from the Oso Bay inflow. Underflow near Oso Bay is cool, highly saline and has DO similar to ambient.

Figs. 2, 3 and 4 use data to show the progression illustrated in Fig. 1 for an initially-thickening plume that evolves into a thinner hypoxic plume. We have shown [4] that vertical entrainment in the spreading far-field of Figs. 2 and 3 is essentially zero, and the only DO resupply occurs via transport within the plume itself. These observations lead to the hypothesis, first illustrated herein, that the isolation time within the spreading far-field is critical to understanding hypoxia development.

5. Isolation Time Scale Defined

To understand the relationship between plume dynamics and DO, it is useful to define the non-dimensional isolation time scale, $\tau_i(x)$, at any position 'x' as

$$\tau_i \sim \frac{T_a(x)}{T_{DO}} \tag{10}$$

where $T_a(x)$ is the advection time to 'x' and T_{DO} is the time-scale for hypoxia to occur. For small τ_i, time is too short for hypoxia to develop, whereas long τ_i is likely to result in hypoxia. The key difficulty is that T_a is inherently non-local, requiring knowledge of the advection path and speeds for the underflow. In naturally-occurring underflows, such data will be poorly known. However, for desalination brine plumes, the advection time scale will be easier to determine as the source water is well characterized and the flow will be generally steady state.

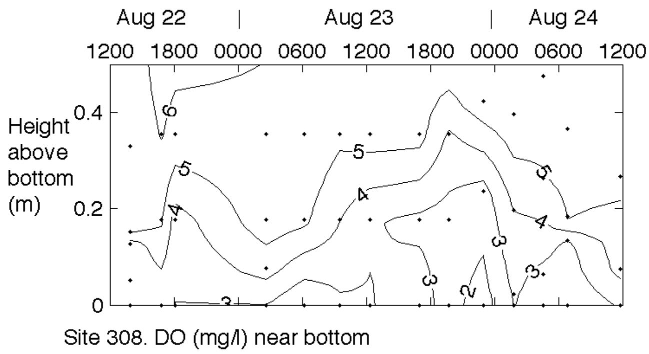

Fig. 4. Evolution of the dissolved oxygen (DO) near the bottom at 2.1 km from Oso Bay (sampling site 308 in [4]). Over the entire course of the study, the DO was hypoxic or near hypoxic. Dots indicate sampling points for raw data used in plotting the contours.

6. Application to a Steady-State Planar Plume

For a simple illustration, consider a confined rectangular plume of breadth B, thickness H and density anomaly $\Delta\rho$ that does not entrain ambient fluid. The plume propagates at Froude number F, such that the advection time to any position from initial position x = 0 is given by

$$T_a(x) \sim \frac{x}{F\sqrt{g'H}} \tag{11}$$

Using a simple mass balance, we arrive at a time-scale over which hypoxia develops for this plume as

$$T_{DO} \sim \frac{(H)(\Delta DO)}{SOD - (H)(NEM)} \tag{12}$$

where ΔDO is the initial dissolved oxygen concentration in the plume above the hypoxic threshold (typically considered 2 mg/l). It follows that

$$\tau_i \sim \frac{x\left[SOD-(H)(NEM)\right]}{F(\Delta DO)\sqrt{g' H^3}} \quad (13)$$

Thus, hypoxia can be expected in the plume at a distance greater than

$$x \geq C\frac{F(\Delta DO)\sqrt{g' H^3}}{SOD-(H)(NEM)} \quad (14)$$

where C is a empirical coefficient. Note that for thin layers (small H) and large SOD, this reduces to

$$x \geq C\frac{F(\Delta DO)\sqrt{g' H^3}}{SOD} \quad (15)$$

Indicating the importance of both H and SOD in determining where hypoxia occurs.

The isolation time provides a general technique can be used to develop more sophisticated models with spatially-varying plume thickness (H), improved characterization of advection time, and DO sources provided by entrainment in the inertial and transitional far-field regions.

7. Comparison to Field Data Scales

Although the plume described in Section 6 is strictly only correct for a planar non-entraining plume, it provides a general scale that, if used carefully, may help predict where hypoxia may be possible. In our field study the gravity current reached the flatter region of the Corpus Christi Bay (~500 m offshore) with the following characteristic scales: $F \sim 0.3$, $\Delta DO \sim 3\,mg/l$, $g' \sim 0.03$, $H \sim 0.2$. Observed NEM values in Corpus Christi Bay are -90 mg m^{-3} hr^{-3} [25]. Observed SOD rates in the bay are 18 mg m^{-2} hr^{-1} [26]. Applying eq. (15) with appropriate unit conversions results in $x \geq 1100\,m$ from the beginning of the shallow slope as an estimated location where the isolation time would be expected. Hypoxia was actually observed between 1000 – 1800m from where the shallower slope commenced. Although the measured plume was neither planar nor entirely non-entraining, the plume thickness was relatively constant and the entrainment was relatively weak so that the F and H estimated from measurements were reasonable indicators of the advection velocity and thickness.

8. Using isolation time to characterize hypoxia

One of the difficulties in dealing with hypoxia in any estuarine water is evaluating the relationship between stratification and hypoxia. This issue may be important in identifying good/bad locations for desalination plants. Existing data sets have been collected under diverse conditions, and the principal data processing is typically a relationship between the measured bottom DO, and the difference between the surface and bottom salinities (known a the salinity anomaly). Engle et al. [27] compiled known data for all Gulf of Mexico estuaries (Fig. 5), showing very little relationship between bottom DO and salinity anomaly. This type of data might be assumed (perhaps erroneously) to indicate that the salinity anomaly is not an important contributor to hypoxia in these systems.

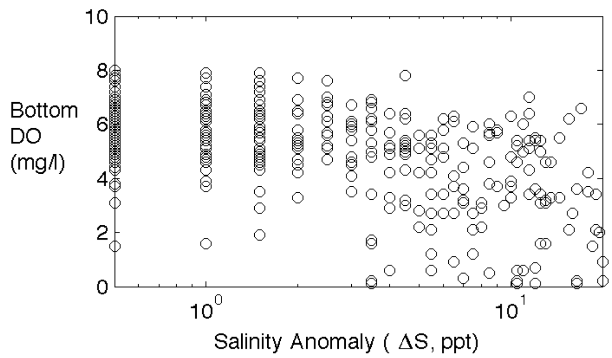

Fig 5. Data for USA Gulf of Mexico estuaries, digitized from Fig. 10 of [27] with a precision of +/- 0.5 ppt and 0.1 mg/l.

If we graph the data from our field study [2,3,4] on the same axes, shown as Fig. 6, the results also show no significant relationship between the salinity anomaly and hypoxia. This result is counter-intuitive to much of the literature, but naturally follows from observing that in Figs. 2 and 3 the highest salinity anomalies are near the outlet of Oso Bay, which has some of the higher DO values. Note that the axes on Fig. 6 provide no clear distinction between the inertial far-field that is dominated by plume entrainment and the spreading far-field dominated by plume erosion.

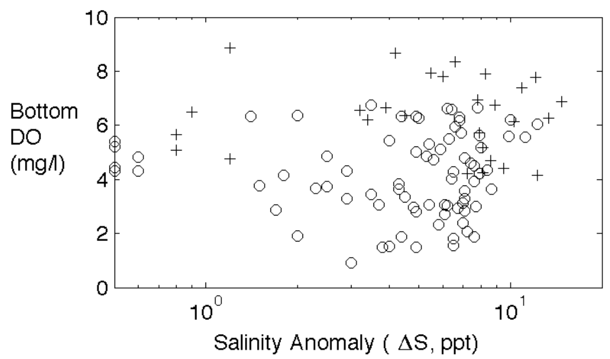

Fig. 6. Symbols: (+) are data points in inertial far-field. (o) are data point in spreading far field. Data from Corpus Christi Bay field study [2,3,4] graphed on the same axes as Fig. 5.

If we use the isolation time computed from eq. 13 on our field data [2,3,4] we see a clear trend shown in Fig. 7, that longer isolation times are associated with lower bottom DO. Thus, investigation of plume advection times relative to DO demands can help explain the scatter in the relationship between stratification and hypoxia.

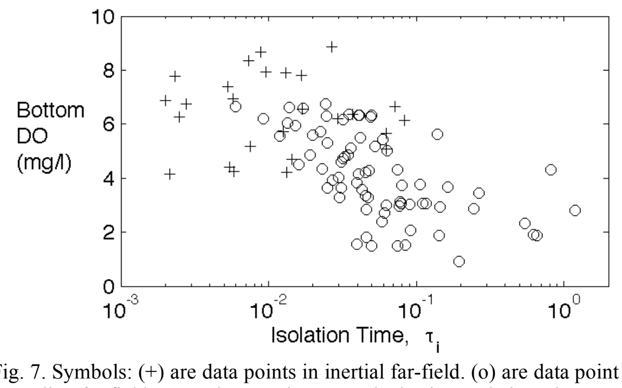

Fig. 7. Symbols: (+) are data points in inertial far-field. (o) are data point in spreading far field. Same data as Fig. 6, graphed using Isolation Time as the ordinate.

9. CONCLUSIONS

A significant indirect impact of desalination brine discharge into an estuary, coastal ocean or embayment may be the development of hypoxia. We have shown that the key parameters in evaluating the propensity for hypoxia are the DO demands in the water column and sediment, combined with the isolation of the plume as it spreads and thins out over the seabed. The change in mixing characteristics from entrainment into the plume to erosion of the plume leads to very different consequences in the DO budget. A lesson from this study is that the ability to model the entraining inertial far-field region of a desalination brine plume should not be taken as indication that the model can represent the spreading far-field region where the physics are fundamentally different.

ACKNOWLEDGMENTS

Discussions regarding Gulf of Mexico hypoxia with Professors Robert D. Hetland Steve F. DiMarco from the Oceanography Department at the Texas A&M University were particularly useful in the present work. They played a significant role in encouraging me to develop the isolation time as a non-dimensional parameter for evaluating hypoxia.

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