DRAFT 15 September 2013

Desalination Plant Entrainment Impacts and Mitigation

Final report submitted to MarielaPaz Carpio-Obeso, Ocean Standards Unit, State Water Resources Control Board (SWRCB) in fulfillment of SWRCB Contract No. 11-074-270, Work Order SJSURF 11-11-019.

By: Dr. Michael S. Foster, Moss Landing Marine Laboratories, Panel Chair (marine ecology)
Dr. Gregor M. Cailliet, Moss Landing Marine Laboratories (marine fishes)
Dr. John Callaway, University of San Francisco (restoration)
Dr. Kristina Mead-Vetter, Consulting Biologist (biomechanics)
Dr. Peter Raimondi, University of California, Santa Cruz (marine ecology)
Dr. Philip J.W. Roberts, Consulting Engineer (Georgia Institute of Technology) (diffuser design)

Background

The SWRCB is developing a policy for addressing environmental impacts from desalination plant intakes and discharges that will be instituted through amendments to the California Ocean Plan (statewide water quality standards). The California Water Code currently requires new or expanding industrial facilities, including desalination plants, to use the "best available site, design, technology, and mitigation measures feasible" to minimize the mortality of marine life (see the Ocean Plan Triennial Review 2011-2013 Work-plan at http://www.waterboards.ca.gov/board_decisions/adopted_orders/resolutions/2011/rs2011_0013_attach1.pdf). The assumption is that the "best site, design and technology" would be employed prior to mitigation measures. Mitigation measures would be applied to compensate for any residual impacts.

A previous Expert Review Panel (ERP, Foster et al. 2012) provided the SWRCB with information on mitigation for residual impingement and entrainment caused by intakes that withdraw water directly from the ocean without any filtration (surface intakes). Foster et al. (2012) suggested the cost of impingement mitigation could be based on a determination of organisms (including weight) impinged and killed at the intake, and their cost per pound, plus their indirect economic value. Mitigation for entrainment could be determined using existing data from studies for power plants and a desalination plant in California, or on new assessments at each plant. Recent assessments of entrainment impacts in California have been based on field sampling and measurements suitable for use in an Empirical Transport Model (ETM) to estimate the Area of Production Foregone (APF; also called HPF or Habitat Production Foregone). Mitigation costs are based on the cost of replacing the production lost ('foregone') to entrainment by producing new, equivalent habitat, restoration that replaces the lost production, or other projects deemed equivalent. Foster et al. (2012) recommended that if new assessments were done, they use the ETM/APF approach because it compensates for the loss of the broad range of organisms impacted by entrainment, not just select groups that have economic value such as fishes, and is science-based. The APF approach has been adopted by California regulatory agencies to determine mitigation for entrainment by power plants.

The previous ERP also outlined a method of determining APF-based mitigation fees that might be used for power plants that are operating on an interim basis. A similar ‘fee’ (cost of mitigation/gallons of water used) could be used for desalination plants because the impingement and entrainment impacts are similar to those that occur at power plants, although the magnitude of the impacts is likely to be smaller in most desalination plants because the volumes of water are smaller. However, the fee was adjusted for power plants relative to the lifetime of their mitigation project because the power plants are operating on an interim basis until they come into compliance with the SWRCB’s Use of Coastal and Estuarine Waters for Power Cooling Policy (OTC Policy). Desalination plants are expected to operate indefinitely so the mitigation fee should not be so adjusted.

Foster et al. (2012) reviewed the efficacy of small-mesh wedge wire screens that could reduce intake impingement and entrainment by surface intakes. They concluded that small mesh screens could eliminate impingement and potentially reduce entrainment of large larvae (screen size 1 – 2 mm), but their effectiveness at reducing entrainment had not yet been well demonstrated in California coastal waters. Thus, how small-mesh screens would affect the determination of APF could not be evaluated.

In 2013, the staff of the SWRCB requested the formation of a new ERP, chaired by Foster and composed of the authors of this report, to focus only on entrainment impacts and mitigation for desalination plants, including potential impacts from discharge diffusers. The tasks for the panel were:

1. Evaluate the potential effects of discharge diffusers on:
    A. organisms entrained into the diffuser plume, and
    B. turbidity.
2. Provide further explanations of the ‘fee’ approach to the cost of mitigation for entrainment impacts caused by desalination plant intakes, including how the cost of mitigation might be adjusted if small-mesh screens were used at the intake.

The panel met twice to discuss the tasks, relevant information, and potential conclusions, and panel members Mead-Vetter, Roberts and Raimondi prepared four reports that are Appendices 1-4 to this report. Appendix 1 examines the likelihood and extent of impacts to organisms entrained into diffusers, and turbidity caused by this entrainment. Appendix 2 critically reviews arguments by Tenera Environmental [Tenera (2012) report to the West Basin Municipal Water District (WBMWD) and submitted to the SWRCB] that entrainment impacts from diffusers are very high. Appendix 3 critically reviews the diffuser design analyses by Jenkins [2013, done for Poseidon Resources and submitted to the SWRCB]. Appendix 4 details approaches to determining mitigation for entrainment impacts and their costs, including comments on approaches suggested by WBMWD (2013) and the potential effects of small mesh screens on APF determination. The panel conclusions below are based on these reports as well as discussions and experience from prior assessments and mitigation for coastal intakes and discharges in California. The panel also received comments on their draft review and conclusions at a public meeting in September, 2013, some of which were incorporated into this report.

The review and conclusions below, unless otherwise noted, are based on a desalination plant that uses a surface intake (i.e., uses ambient ocean water that includes organisms naturally occurring within the water at the intake location) and discharges the undiluted brine water through diffusers into the ocean.

Review and Conclusions

1. Discharge diffusers

A. *Effects on entrained organisms*

DIFFUSERS

To reduce environmental impacts from the disposal of high salinity brine water into the ocean, the Southern California Coastal Water Research Project (SCCWRP 2012) recommended the brine water be diluted to a salinity of no more than 5% above ambient at the point of discharge using diffusers on the discharge. Diffusers accomplish this dilution by increasing entrainment of surrounding, ambient salinity water that rapidly mixes with the brine water. The desired dilution is achieved with mixing on the order of 20 ambient to 1 brine within 100 meters of the discharge, the size of the mixing zone suggested by SCCWRP (2012). The SCCWRP report pointed out that there is no published evidence of mortality due to diffuser jets, but suggested further analyses and experiments were needed. Foster et al. (2012) did not consider the issue. Tenera (2012) subsequently argued for the assumption that all fish larvae entrained by discharge diffusers are killed, and Jenkins (2013) developed diffuser designs that might reduce mortality.

The reviews and analyses in Appendix 1 indicate damage to organisms caused by diffuser turbulence will likely be low because only 23-38% of the entrained water is exposed to potentially damaging turbulence, and exposure to such turbulence is on the order of seconds. Literature reports of damage to larvae caused by turbulence are generally based on longer exposure times. Moreover, the need for and efficacy of diffuser designs suggested by Jenkins (2013) to reduce turbulence are questionable (review in Appendix 3).

While the hydrodynamics of currently used desalination plant diffusers, combined with information on larval sizes and exposure times, indicate damage and mortality to entrained organisms will be low, experiments are recommended to test these conclusions. Field monitoring that examines the magnitude of the effects, including those caused by the interaction of turbulence with salinity and other environmental conditions that may be affected by the mixing process, would be especially informative.

DIFFUSERS VERSUS IN-PLANT DILUTION

For the purposes of this ERP, in-plant dilution would require the intake of additional source water that would be used to mix with and dilute brine water within a desalination plant prior to discharge. It is a potential alternative to dilution with diffusers at the discharge. Like mixing with diffusers, in-plant dilution would require approximately 20 times the amount of water used for freshwater extraction, and the dilution water would be subject to entrainment impacts. SCCWRP (2012) mentioned the mortality of organisms in the dilution water caused by intake pumps, and that this might be reduced with pumps that reduce turbulence. It was noted, however, that the practicality of such pumps for use in a desalination plant has not been demonstrated. In addition to practicality, we are unaware of existing pumps that can move the amounts of water required and also reduce turbulence at the scales needed to protect very small organisms.

Given some impacts occur from entrainment into diffusers, how do these compare with impacts from the in-plant mixing process? This cannot be answered with certainty, especially given the lack of information on possible systems that would reduce in-plant entrainment mortality. In the absence of data to the contrary, it has generally been assumed that entrainment mortality in the water used to cool once-through coastal power plants and the water used for freshwater extraction in desalination plants is 100%, due primarily to passage through pumps and elevated temperatures in the former, and pump passage and the freshwater extraction process in the latter. It is assumed in-plant dilution water would be separated from the intake flow before passing through the freshwater extraction process. The organisms in the dilution water, however, will likely still be impacted by:

1. Contact with the intake structure and removal by filter feeding organisms that foul the structure.
2. Passage through intake pumps.
3. Mixing with brine water.
4. Passage through the discharge structure (as in 1.)

Further impacts may occur depending on increases in water temperature while in the dilution system, and if the diluted water is discharged into a habitat different from the habitat at the intake (reduced survivorship due to different environment, predators, food, etc.).

Presumably all the in-plant dilution water would experience these impacts. As previously noted, pump designs that might reduce mortality through intake pumps have not been evaluated under desalination plant operating conditions. We are also unaware of designs or technology for facilities that would mix the dilution and brine water to minimize mechanical and salinity impacts. In contrast, the impacts of dilution at the discharge are limited to exposure to the discharge jets and possibly to variable salinity. As reviewed in Appendix 1, modeling studies and related empirical data indicate that although experiments are needed, 38% or less of the water entrained by diffusers is likely to be impacted, and impact is likely reduced within this water due to short exposure times (10-50 seconds).

Until relevant information, designs and technology are available that show otherwise, it is reasonable to assume that impacts to organisms in the water entrained for dilution by diffusers are likely less, and perhaps much less, than impacts to dilution water used for in-plant dilution.

B. *Effects on turbidity and sedimentation*

Diffusers could increase turbidity and sedimentation by entraining fine sediment into the discharge plume, by the discharge of organisms killed during the desalination process, and as a result of the plume slowing coastal currents. Turbidity increases could have negative effects on organisms living on the bottom via reduced light and increased burial and abrasion. Increases in turbidity could variously alter predation and feeding in the water column (Appendix 1). The question is: are changes in turbidity and sedimentation caused by desalination plant discharge diffusers likely to have important ecological consequences? Tenera (2012) argued that they would cause “significant environmental damage” based on the effects of the discharge at the San Onofre Nuclear Power Plant (SONGS). The SONGS discharge volume is, however, over an order of magnitude larger than any existing or proposed desalination plant in California, and the diffuser design is much different (e.g., 20^0 angle from horizontal versus 60^0 for typical desalination plants). SONGS is not a reasonable comparison (see Appendix 2).

The review and analyses of possible turbidity effects in Appendix 1 indicates that given a 60^0 elevation of the diffusers, entrainment velocities along the bottom are only on the order of 2 centimeters/sec at less than 1 meter from the jets, and rapidly fall below typical ambient velocities beyond 1 meter. Very little sediment suspension would be expected under these conditions. The discharge will contain organisms killed within the plant but given the volume of water affected and mixing processes at discharge, effects are likely small. It also seems unlikely that the relatively small desalination plant discharges could significantly slow coastal currents.

It therefore seems unlikely that increases in turbidity and sedimentation caused by desalination plant discharge diffusers would have significant environmental effects. Like diffuser entrainment impacts discussed previously, however, the accuracy of this conclusion should be examined with field measurements around operating diffusers. Such measurements could be combined with the benthic monitoring recommended by SCCWRP (2012) for the effects of increased salinity on the sea floor.

2. Mitigation determination and cost

As mentioned in Background above, Foster et al. (2012) recommended an ETM/APF approach to determining mitigation for desalination plant intake entrainment impacts. This approach has the ecologically important advantage of estimating impacts to undervalued species that are often not considered in other approaches to determining impacts. ETM/APF results in a currency of impact, area needed to compensate for entrainment impacts, specifically designed to address ecosystem-scale impacts rather than impacts to a particular species or group of species. If habitat creation or restoration is not feasible, the method provides a measure of impact importance and a cost basis for other mitigation alternatives. ETM/APF has been almost universally used in power plant entrainment studies and mitigation considerations in California (the method and advantages are discussed in more detail in Appendix 4).

Mitigation for desalination plant entrainment impacts could be determined from new studies at each desalination facility or by using information from previous studies to determine a mitigation fee based on the volume of water entrained by the facility. Using data from prior studies may be preferred given the small volumes of water used relative to power plants, the cost of new studies, and because prior studies suggest the resources lost due to entrainment scale linearly with volume (details in Appendix 4). The table in Appendix 4 provides the relevant data from previous studies in California. For example, the average cost of replacing estuarine habitat lost to entrainment is $38,520.00/MGD (Million Gallons of Water entrained per Day). The cost of mitigation for a desalination plant permitted to use 10 MGD would therefore be $385,520.00. The estimate would need to be increased to adjust for inflation since the original studies were done, and to include project management and administrative costs. The latter should be kept to a minimum to optimize ‘in the ocean’ benefits. The fee should also be increased to include the cost of monitoring the success of projects as monitoring costs are an integral part of any mitigation project.

WBMWD (2013) has suggested calculating mitigation based on some variations of the ETM/APF approach that include using a single species and a “Whole Life Cycle Analysis” approach to discount younger larvae. As discussed in Appendix 4, a single species approach is unlikely to be representative of the range of species that will are impacted, and this method eliminates the ability to calculate confidence intervals for APF. Moreover, WBMWD (2013) appears to incorrectly calculate proportional mortality, and does not show the equations needed to fully evaluate the whole-life approach (brief review and critique in Appendix 4).

As stated previously, the efficacy of small-mesh screens for reducing intake entrainment was reviewed in Foster et al. (2012) and remains to be well demonstrated for California coastal waters. Such screens would eliminate impingement of large organisms. However, if screens did reduce entrainment of large larvae this would have little impact on APF because APF is based on the proportional loss of *all* larvae, not just large ones, and large larvae are usually a very small percentage of all larvae. An analysis of impact reduction and methods for reducing APF based on the reduction are given in Appendix 1. For the small mesh screens being considered, the reduction in entrainment mortality (and APF) is likely to be less than 1%.

Literature Cited

Foster, M.S., Cailliet, G.M., Callaway, J., Raimondi, P. and Steinbeck, J. 2012. Mititation and Fees for the Intake of Seawater by Desalination and Power Plants. Report to State Water Resources Control Board, Sacramento.

Jenkins, S.A. 2013. Dilution Issues Related to Use of High Velocity Diffusers in Ocean Desalination Plants: Remedial Approach Applied to the West Basin Municipal Water District Master Plan for Sea Water Desalination Plants in Santa Monica Bay. Scott A. Jenkins Consulting, Poway.

SCCWRP (Southern California Coastal Water Research Project). 2012. Management of Brine Discharges to Coastal Waters - Recommendations of a Science Advisory Panel. Technical Report 694 to the State Water Resources Control Board, Southern California Coastal Water Research Project, Costa Mesa, CA.

Tenera (Tenera Environmental). 2012. Biological and Oceanographic Factors in Selecting Best Technology Available for Desalination Brine Discharge. Tenera Environmental, San Luis Obispo.

WBMWD (West Basin Municipal Water District). 2013. Intake entrainment 5 step calculation (illustrated PDF submitted to SWRCB, April 5, 2013). West Basin Municipal Water District, Carson.

Appendix 1. to Foster et al. (2013)

The Effects of Turbulence and Turbidity Due to Brine Diffusers on Larval Mortality: A Review

By:

Philip J. W. Roberts

Consulting Engineer

Atlanta, Georgia, USA

Kristina Mead- Vetter

Consulting Biologist

Palo Alto, California USA

Prepared for

State Water Resources Control Board

Sacramento, California

CONTENTS

EXECUTIVE SUMMARY

The purpose of this report is to investigate the potential effects of turbulence and turbidity caused by brine diffuser jets on larvae entrained into the jets. The effects of turbulence were modeled using established data on jet turbulence characteristics and applied to a typical diffuser based on that for Perth, Australia. Biological data on turbulence effects were compiled and summarized. The effects of turbidity were also summarized from the literature.

Turbulence issues were first addressed. In a typical brine diffuser with a 60° nozzle inclination, the jet rises to a terminal level then falls back to the lower boundary where it spreads as density current. The regions of high shear stress are confined to the rising portions of the jet; the descending portions have much lower shear stresses. The flow continues to be turbulent after impacting the bottom for some distance (the near field) after which it becomes laminar again. Using well-known equations, the flow properties of the rising portion of the jet are estimated. For example, the length of the rising portion of the jet is about 8 m. The greatest turbulence intensity is on the jet centerline, and it decreases rapidly outward. The Kolmogorov length scales (an estimate of the smallest turbulent eddy sizes) range from 0.01 mm to 0.05 mm near the nozzle to 0.1 mm to 0.5 mm at the terminal rise height. This suggests that some eddies will be similar in size to or smaller than the larvae, which suggests that they have the potential to inflict damage. However, exposure of the larvae to these high levels of turbulence intensity will be brief; the travel time on the centerline is typically on the order of 10 seconds, and near the jet edge is on the order of 50 seconds. Therefore, organisms entrained and traveling near the jet edges will undergo lower intensities but for longer times. Overall, the area of high shear impacted by the diffusers is relatively small. A summary of published effects of turbulence on gametes and larvae is given in Appendix A.

Brine diffusers are designed to eject the effluent at high velocities. This results in entrainment of seawater into the jets that mixes with and dilutes the effluent. Some issues relating to this entrained flow were addressed, in particular the magnitude and spatial variation of the entrained flow, the magnitude of the entrained flow that is subject to high turbulence intensity and shear and the possibility for the entrained flow to suspend and ingest bottom sediments.

The entrained flow velocities are quite low and decrease rapidly with radial distance from the jets. For example, for a typical diffuser, the entrainment velocity at 1 m from the jets is about 2 cm/s. The entrainment velocity therefore falls to below typical ambient oceanic velocities within less than about 1 m from the jets.

Because diffuser nozzles are typically raised about 1 m off the seabed, it is highly unlikely that the entrainment velocities will be high enough to suspend and ingest bottom sediments and cause an increase in turbidity.

The dilution process in a dense brine diffuser jet occurs in ascending and descending phases. The ascending phase is driven by the source momentum flux and is the region of relatively high shear and turbulence intensity; this is the region where larval damage, if it occurs, is most likely. The descending portion has much lower shear and turbulence intensity and larval damage is unlikely there. Most of the dilution occurs in the descending phase.

The ratio of dilution at the terminal rise height to that at the impact point is approximately equal to the ratio of the volume of water entrained into the jet region to the total water entrained. This ratio is about 0.38, or 38%. Similarly, the ratio of jet-induced volume to total volume up to the end of the near field is about 0.23, or 23%. The actual ratio will depend on whether the suggested dilution requirement of 20:1 is applied at the impact point or at the end of the near field. It could be applied at the end of the near field, which was suggested by SCCWRP (2012) to be 100 m from the diffuser.

Therefore, the volume of water that is entrained for dilution that is subject to relatively high turbulence intensities and shear stresses is about 23 to 38% of the total entrained volume.

This water that is entrained into the diffuser jets can be compared to that entrained into a water intake for in-pipe dilution of the same overall dilution. The volumes of water entrained in each case are approximately the same, but for the diffuser, only 23-38% is subject to high shear stresses and for short times, whereas all in-plant dilution water may be subject to high shear stresses for longer times.

Turbidity should not be a concern if a 60° nozzle elevated more than 1 meter above the bottom is used because sediment entrainment is likely to be negligible with little impact on the benthos (Einav et al. 2002). This was not modeled mathematically; however, a review of the literature (provided in Table 1) suggests that turbidity can mitigate some of the detrimental effects of turbulence. As with turbulence, there may be different effects on different species and there may be effects of size. For example, some fish appear to experience a reduction in prey perception due to the decrease in light and visibility caused by turbidity. However, other species experienced enhancement of feeding at moderate to high turbidities due to increased prey contrast. Turbidity may also provide refuge from predation. Given the diffuser jet angle and the low water velocities along the benthos, it seems reasonable to expect that little sediment will be suspended, and that effects of turbidity will be minimal.

LIST OF FIGURES

LIST OF TABLES

1. JET TURBULENCE EFFECTS

It has been suggested that larvae entrained into the high velocity turbulent jets of brine diffusers could be subject to injury, possibly mortality, due to effects of turbulence and shear. The turbulence generated by brine diffusers is discussed in this section, in particular the spatial variations of turbulence intensity and length scales (eddy sizes) of the turbulence.

1.1 Dense Jet Diffusers

The main flow characteristics for a dense jet typical of a brine discharge into a stationary environment are shown in Figure 1. The negative buoyancy of the jet causes it to reach a terminal rise height and then fall back to the lower boundary where it spreads as a density current. Vertical jets fall back onto themselves when discharged into a stationary environment, resulting in lowered dilutions, so inclined jets are more commonly used. A 60° nozzle inclination seems to have been adopted as the de facto standard for diffuser designs. The dynamics and mixing of turbulent dense jets have been the subject of intense research (see, for example the bibliography in Lai and Lee, 2012). Some of the major features are reviewed below.

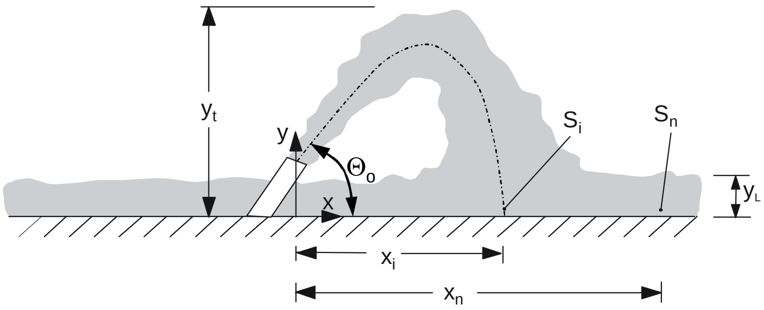

Figure 1. Schematic depiction of dense jet diffuser

In order to achieve high dilution and rapid dilution of the brine, the effluent is released as a high velocity jet. Typical discharge conditions, for example the Perth, Australia diffuser (Marti et al., 2011) is a jet velocity of 4.1 m/s from a 13 cm diameter nozzle. The brine density is 1049 kg/m^3 and the ambient density about 1025 kg/m^3. The effluent salinity is about 67 psu, and the ambient salinity about 35 psu. These are typical numbers for seawater desalination with reverse osmosis plants that result in approximately equal volumes of potable water and brine, i.e. the salinity in the effluent is approximately doubled compared to the intake. In that case, a dilution of 20:1 will result in a reduction in salinity to 5% over the ambient level, as recommended by the expert panel (SCCWRP, 2012).

Figure 2 shows a laser-induced fluorescence (LIF) image of a laboratory dense jet. The colors represent instantaneous tracer concentrations, or salinity. As discussed further in Section 2, the regions of high shear are confined to the rising portions of the jet; the descending portions are lower shear. The flow continues to be turbulent after impacting the bottom for some distance (the near field) after which it relaminarizes. All of the major properties of the jet, rise height, impact distance, dilution, etc. can be estimated by application of well-known formulas that have been extensively used in brine diffuser design (for example, Roberts et al., 1997).

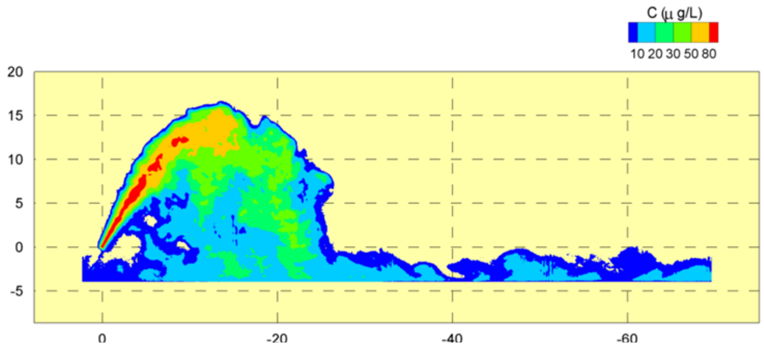

Figure 2. Laser-induced fluorescence image of typical dense jet discharge

The regions of the flow most likely to result in shear-induced impacts on larvae are the rising portion of the jet up to the terminal rise height. In the following, we make estimates of jet flow properties in this region.

The flow properties are primarily determined by the densimetric Froude number of the jet:

$$\mathsf{F} = \frac{u}{\sqrt{g_o' d}} \tag{1}$$

where u is the jet exit velocity, g_o' the modified acceleration due to gravity, and d the nozzle diameter. The relevant equations (Roberts and Abessi, 2013) for geometrical properties are:

$$\frac{y_t}{d\mathsf{F}} = 2.2; \qquad \frac{x_i}{d\mathsf{F}} = 2.4; \qquad \frac{x_n}{d\mathsf{F}} = 9.0 \tag{2}$$

and for dilution:

$$\frac{S_i}{\mathsf{F}} = 1.6; \qquad \frac{S_n}{\mathsf{F}} = 2.6 \tag{3}$$

where (Figure 1) y_t is the terminal rise height, x_i the location of the jet impact point (the location of the minimum dilution on the lower boundary), x_n the length of the near field, S_i the dilution at the impact point, and S_n the near field dilution. Eqs. 2 and 3 apply when the jets are fully turbulent, i.e. the jet Reynolds number, $\mathsf{Re} = ud/\nu$ where ν is the kinematic fluid viscosity is greater than about 2000, and the Froude number is greater than about 20, when the dynamical effect of the source volume flux becomes negligible.

The flow turbulence properties can be estimated up to the terminal rise height by assuming the flow behaves like a pure jet up to that point. For example, for the Perth diffuser, the Froude number is about 24, d = 0.13 m, so the rise height is about 7 m. For a 60° nozzle angle, and assuming a straight trajectory to this point, the length of the trajectory is about 8 m.

Within a turbulent jet, beyond the zone of flow establishment, which is about 6d long, the centerline velocity decreases rapidly according to (Fischer et al., 1979):

$$u_m = 6.2u\frac{d}{x} \tag{4}$$

The half-width of the jet, defined as two standard deviations of a Gaussian velocity distribution, increases linearly with distance according to:

$$w = 0.15x \tag{5}$$

Combining Eqs. 4 and 5, we see that the average mean shear in the jet $d\bar{u}/dr \approx u_m/w$ is:

$$\frac{d\bar{u}}{dr} \approx \frac{u_m}{w} \approx 41\frac{ud}{x^2} \tag{6}$$

So it decreases rapidly with distance from the nozzle. Note that the mean shear on the jet centerline is zero.

The turbulence properties in the jet can be estimated from the experimental data of Webster et al. (2001). Their graphs show that the relative turbulence intensity on the centerline, $u'/u_m \approx 0.3$. The intensity decreases with radial distance to zero at the edge of the jet, defined approximately by Eq. 5.

The size of the small-scale (Kolmogorov) eddies can be estimated from:

$$\eta : \left(\frac{\nu^3}{\varepsilon}\right)^{1/4} \tag{7}$$

where ν is the kinematic viscosity of seawater and ε the energy dissipation rate, that can be approximated as:

$$\varepsilon : \frac{u'^3}{l_L} \tag{8}$$

where l_L is a measure of the largest (energy containing) eddies in the jet. According to Wygnanski and Fiedler (1969) these length scales also increase linearly with distance from the nozzle and vary radially across the jet. On the centerline, $l_L : 0.016x$, i.e. about 1/12 of the jet width.

Finally, combining the above equations we find:

$$\frac{\eta_c}{x} = 0.24\,\mathrm{Re}^{-3/4} \tag{9}$$

where $\mathrm{Re} = ud/\nu$ is the jet Reynolds number and η_c the size of the Kolmogorov eddies on the jet centerline.

The turbulence intensity and turbulent length scales vary radially across the jet and this variation is now considered.

Near the jet edge, $l_L : 0.03x$ according to Wygnanski and Fiedler, i.e. about 1/25 of the jet width, and the turbulence intensity is about $\tilde{u}/u_m \approx 0.04$ according to Webster et al. (2001). Combining Eqs. 7 and 8 we can estimate the ratio of the Kolmogorov scale on the centerline to that at the jet edge as:

$$\frac{\eta_c}{\eta_e} = \left\{ \frac{\left(l_c/l_e\right)}{\left(\tilde{u}_c/\tilde{u}_e\right)^3} \right\}^{1/4} \approx 0.2 \tag{10}$$

where the subscripts *c* and *e* refer to the jet centerline and edge, respectively. Eq. 10 indicates that the Kolmogorov scales at the jet edge are about five times larger than on the centerline.

1.2 Application to Perth Outfall

For the Perth brine diffuser, we have: u = 4.1 m/s, d = 0.13 m, so assuming $\nu = 10^{-6}$ m^2/s, Re = 5.3x10^5, and the Kolmogorov scale on the centerline ranges from about 0.01 mm near the nozzle to 0.1 mm at the terminal rise height. The Kolmogorov scales at the edge of the jet range from about 0.05 mm near the nozzle to about 0.5 mm at the terminal rise height. The mean shear rates range from about 21 sec^{-1} near the nozzle to 0.2 sec^{-1} at the terminal rise height.

Travel times of larvae entrained into the jet will vary, depending on whether they travel on the centerline, on the edge, or in between. On the centerline, the velocity decreases according to Eq. 4 so the travel time up to the terminal rise height is given approximately by:

$$t = \int_0^L \frac{x}{6.2ud}dx = \frac{L^2}{12.4ud} \tag{11}$$

where L is the length of the trajectory up to the terminal rise height. For the Perth diffuser this corresponds to a travel time of about 10 seconds. The mean velocity profiles of Webster et al. (2001) show that the jet velocity is greater than about 20% of the maximum over about 80% of the jet width. Therefore, closer to the jet edges, travel times will be about 50 seconds. Organisms entrained and traveling near the jet edges will undergo lower intensities (larger eddies) but for longer times.

Clearly, the smallest length scales in the jet will be smaller than the smallest organisms of interest (for example, fish and invertebrate larvae, and these eddies should not cause physical damage to larvae. In turbulence, there is a continuous spectrum of eddy sizes and turbulent kinetic energy from the smallest (Kolomogorov) to the largest (energy-containing) eddies. For the typical jets discussed above, this ranges from about 0.01 mm to 0.24 m, so there will be some eddies of size comparable to the organism sizes that may affect them. It should be noted, however, that the strain rates (and shear stresses) are maximum at the Kolmogorov scale and decrease as the eddy size increases. Typical Kolmogorov scales in the ocean are of order a few millimeters so incremental impacts of the jets could be expected to be confined to fairly small volumes.

Overall, the area of high shear impacted by the diffusers is relatively small and transit times through this region relatively short. Thus, it seems reasonable to expect that, while the larvae that experience the highest shear will most likely experience lethal damage, the overall increase in mortality integrated over the larger area will be low.

2. DIFFUSER ENTRAINMENT

2.1 Introduction

In desalination projects, the word entrainment arises in two contexts. It refers to flow drawn into intakes, and, in the jets and plumes that arise in brine diffusers, it refers to the flow induced by velocity shear at the edge of the jet. This flow, commonly referred to as entrained flow, mixes with and dilutes the effluent stream. In this section we consider issues related to the flow entrained into typical brine diffuser discharges. The issues considered are the magnitude and spatial variation of the entrained velocity, the magnitude of the entrained flow expected to be subjected to significant shear and turbulence effects, and possible effects on sediment entrainment.

2.2 Entrainment Velocity

The concept of jet entrainment is illustrated in Figure 3. The jet (or plume) entrains, or drags in, external fluid which then mixes with and dilutes the jet.

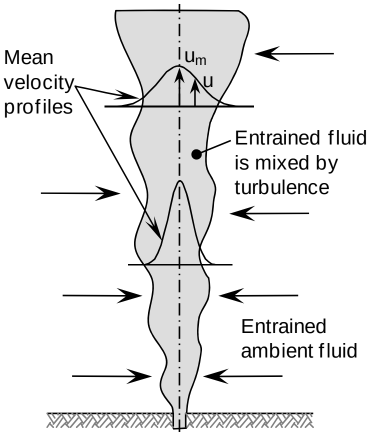

Figure 3. Entrainment and dilution in a simple jet

It can be shown that the velocity at which flow is entrained into the jet is given by:

$$u_o = \alpha u_m \tag{12}$$

where u_o is the entrainment velocity at a radial distance $r = b_w$ from the jet centerline and b_w is defined from the usually assumed radial velocity variation:

$$\frac{u_r}{u_m} = \exp\left\{-\frac{r^2}{b_w^2}\right\} \tag{13}$$

where u_r is the entrainment velocity at radial distance r. The length scale b_w grows linearly with x according to (Fischer et al., 1979):

$$b_w = 0.107x \tag{14}$$

The variation of the entrained velocity u_e with radial distance r beyond the edge of the jet can be determined by continuity:

$$u_o 2\pi b_w = u_e 2\pi r$$

or

$$u_e = u_o \frac{b_w}{r} \tag{15}$$

i.e. the entrained velocity decreases rapidly with distance from the jets in inverse proportion to the distance r.

Combining Eqs. 4, 12, 14, and 15, we find:

$$u_e = 6.2x0.107\alpha \frac{ud}{r}$$

Assuming $\alpha = 0.0535$ (Fischer et al., 1979), this becomes:

$$u_e = 0.035 \frac{ud}{r} \tag{16}$$

In other words, the entrainment velocity is constant with x, the distance along the jet, but decreases rapidly in the radial direction. The entrainment velocity at any location depends only on the source momentum flux of the jet, which is proportional to ud.

Now we apply this result to the Perth diffuser as an example. As previously stated for this diffuser, u = 4.1 m/s, and d = 0.13 m, yielding:

$$u_e = \frac{0.019}{r} \quad \text{m/s} \tag{17}$$

So, at a distance of 1 m from the jet centerline, the velocity has fallen to about 2 cm/s, already smaller than typical oceanic velocities.

For a diffuser port elevated about 1 m from the seabed, these velocities will be too small to scour and entrain sediment.

2.3 Entrainment Volume

We consider now the volume of entrained water that is subject to high turbulence intensities and shear stresses.

As can be seen in Figure 2, the dilution, entrainment and mixing in a turbulent dense jet occurs in the ascending and descending phases of the flow. The rising portion is driven by the momentum flux of the discharge (although the terminal rise height also depends on the source buoyancy flux). This is a region of relatively high shear and turbulence intensity as discussed in the previous section. The descending portion is buoyancy-driven due to the density difference between the effluent and ambient water. This is a partially plume-like flow and partially gravitational diffusion descending from a relatively large area source at the jet top. The role of the source momentum flux in effecting dilution is therefore two-fold: First, it causes entrainment in the rising portion of the jet, and second it elevates the jet in the water column to some height where it can then descend and effect further mixing. The width of the descending portion is much broader than of the rising jet, and the velocities much slower, so the mean shear and turbulence intensities in the descending portion are much lower than in the rising jet region. These features can be seen in Figure 2 and in the LIF videos at:

http://www.youtube.com/watch?v=_qUo-tyRcFI
http://www.youtube.com/watch?v=TCZV2gVkpfg

The mixing and turbulence in the descending region is therefore much gentler than in the rising portion.

Most of the dilution occurs in the descending region, however, as can be seen by comparing the equation for dilution at the terminal rise height (Roberts and Abessi, 2013):

$$\frac{S_t}{F} \approx 0.6 \qquad (18)$$

with the equations for the impact dilution S_i and near field dilution S_n (Eq. 3). Because all dilutions scale with the jet densimetric Froude number, the ratio of these dilutions is constant. For example, the ratio of dilution at the terminal rise height to that at the impact point = 0.6/1.6 = 0.38, i.e. the terminal height dilution is 38% of the impact dilution. Similarly, the ratio of terminal height dilution to near field dilution is 0.6/2.6 = 0.23, i.e. the terminal height dilution is 23% of the near field dilution.

Because it is the entrained flow that causes the dilution, the ratio of entrained water by the rising jet to the total entrained flow is also approximately equal to (but less than) the dilution ratios. For example, the ratio of flow entrained into the high turbulence jets to the total flow entrained up to the impact point is less than 0.38; and the ratio of flow entrained into the high turbulence jets to the total flow up to the end of the near field is less than 0.23.

The actual ratio for a particular diffuser will depend on how the proposed regulations are interpreted: specifically whether the suggested dilution requirement of 20:1 is applied at the impact point or at the end of the near field. If at the end of the near field, which will typically lie within the SCCWRP (2012) recommended mixing zone of 100 m, the percent of additional fluid entrained into the flow will be on the order of 23%.

Clearly, the volume entrained into diffuser jets that is subject to high stresses and turbulent intensities to effect a particular dilution is much smaller than that required for the same dilution via entrainment into an intake. The intake flow may be subject to higher stresses and therefore larval mortality.

3. TURBIDITY

3.1 Introduction

The following is a summary of the literature on the effects of turbidity on larvae. Most of the included experiments are laboratory investigations rather than field studies.

3.2 Review

Coastal turbidity is common in nature, from natural phenomena such as phytoplankton blooms and weathering, and from anthropogenic causes, such as construction, mining, and agriculture, which can lead to high sediment loads especially during storm water runoff.

Effects of the turbidity can vary. Many of the effects stem from the fact that particles in the water column scatter light, and thus reduce the amount of available light. This can affect fish feeding behavior, for example, because the fish will not see their prey items until they are much closer. The reduction in light levels can also affect the growth of submerged aquatic plants, such as kelp and other algae. Other potentially serious effects of turbidity include reduction in pumping and abnormal development in clams, fouling of fish gills, and scouring of aquatic plants.

To address these issues, the US EPA issued a criterion for protecting aquatic life that “settleable and suspended solids should not reduce the depth of the compensation point for photosynthetic activity by more than 10 percent from the seasonally established norm for aquatic life” (EPA 1988). However, this can still cover a range of turbidity that could have deleterious effects. California’s effluent limitations specify that effluents can’t have a turbidity greater than 225 NTU at any time, that weekly averages must be less than 100 NTU, and that monthly averages must be less than 75 NTU (California EPA 2012).

In most of the experiments profiled in this report, the desired turbidity is created by adding kaolin, chalk, Fuller’s earth, or silt. Early experiments simply added 0.1-4.0 g/L of the substance in question; later work aimed to define turbidity in terms of Nephelometric Turbidity Units (NTU), which measure light scatter from the particles. This, in turn, depends on particle size, shape, and other characteristics. In the field, coastal oceanographers use a Secchi disk, a black and white disk that is lowered into the water until it can no longer be seen. This depth is the point at which 18% of the available light remains. This number is recorded as a measure of the transparency of the water (inversely related to turbidity). Researchers and water quality experts also measure the optical transmittance of the water.

A review of the literature (provided in Table 1) suggests that as with turbulence, there may be different effects on different species. Furthermore, there may be effects of size. For example, some fish (especially larger fish; Chesney 1989) appear to experience a reduction in prey perception due to the decrease in light and visibility caused by turbidity (Vineyard and O’Brien 1976). Larger fish (or at least fish with larger eyes) tend to see farther in clear water, and so experience a greater diminution of prey perception distance than smaller fish.

On the other hand, turbidity has been shown to enhance some aspects of fish biology. Boehlert & Morgan (1985) studied larval Pacific herring *Clupea harengus pallasi* and found enhancement of feeding at moderate to high turbidities (500 to 1000 ppm). They attributed this result to increased prey contrast. Turbidity may also provide refuge from predation (Bruton 1985) that turbidity can actually mitigate deleterious effects of turbulence (Chesney 1989).

As with turbulence, the effects of turbidity vary with both the magnitude and the length of time of exposure. The literature indicates that chronic and low levels of turbidity (as low as 2-3 NTU) are correlated with adverse effects on aquatic life, such as primary productivity. However, turbidities of 3-4 NTU are common along the coast, and should probably be considered background (Huang et al., 2013). The reactive distance of fish decreases with increasing turbidity levels, with effects on fish growth and feeding generally reported around 20-30 NTU for exposures lasting a day or more, and around 50 NTU for exposures lasting less than one day. At the same time, several studies have shown that fish can feed successfully even at relatively high turbidities. In fact, it appears that juvenile fish are adapted to and benefit from higher levels of turbidity in estuaries.

In the case of desalination plants, some have voiced concerns that the release of the waste water near the benthos could potentially suspend substantial amounts of sediment, which could have harmful effects on organisms in the water column. However, the likeliness of this scenario can be minimized by the location of the desalination plant in high energy coastal regions (Einav et al. 2002) and by an appropriate choice of angle of the diffuser jet that would direct the outflow to the sea surface (Einav et al. 2002). Furthermore, diffuser nozzles are typically elevated at more than 1 m from the seabed. For a typical diffuser, the entrainment velocity at 1 m from the jets is about 2 cm/s. The entrainment velocity therefore falls to below typical ambient oceanic velocities within less than about 1 m from the jets. Given the proposed diffuser jet angle and low entrainment velocities, it seems reasonable to expect that a minimal amount of sediment will be suspended. Thus, the diffuser jets are not expected to materially affect turbidity.

Table 1. Effect of turbidity on fish and invertebrate larvae

Animal	Lab/Field	Amount of turbidity	Effects	Authors
Striped bass larvae *Morone saxatalis* (5 DAH old)	Lab (76 L tanks, 4 larvae/L). EXpts ran for up to 21 days	50, 100, 150 ppm kaolin (40, 90, 130 NTU)	Still had 88-92% survival after 20 days*	Chesney 1989
rainbow smelt larvae (*Osmerus mordax*)	Field	10->100 NTU	Larvae seemed to use vert and long circ in estuary to remain in turbid areas	Dauvin, J.-C. and J. J. Dodson (1990)
Fathead minnow *Pimephales promelas*	lab	11.01 +/- 0.34 NTU	Turbidity reduces antipredator behaviors (more time spent in dangerous hábitat)	Abrahams and Kattenfeld 1997
Yellow perch *Perca flavescens* (predator)	lab	11.01 +/- 0.34 NTU	Turbidity affects preferred size of prey (no longer biased toward smaller fish)	Abrahams and Kattenfeld 1997
Bluegill sunfish *Lepomis macrochirus*	lab	10 NTU	Reactive distance (to largemouth bass) declined from 200 cm to 23 cm	Miner and Stein 1996
Clam *Mercenaria mercenaria*	Lab, rotating wheel of small buckets	Up to 4 g/L kaolin, chalk, Fuller's earth, or silt	Decreases development to straight hinge stage at conc >0.75 g/L	
oysters	field	Natural silt from human dedging operation	No eff on mortality, physiol condition, setting	Lunz (1938)
oysters	lab	0.1 -4 g/L Silt, kaolin, chalk, Fuller's earth	57% decrease in pumping rate of adults if 0.1g/L silt	Loosanoff and Tommers (1948)
zooplank				

DAH = days after hatching

*turbidity ameliorated some effects of turbulence, had lower growth rate; no turbidity without turbulence (logistics: needed turbulence to keep particulates suspended); feeding and light important.

4. TURBULENCE AND SHEAR STRESS

4.1 Introduction

This section reviews the literature on the effects of turbulence and shear stress on aquatic organisms. Most of the data are from laboratory experiments that exposed various types of larvae to controlled levels of laminar shear stress in a Couette cell, or to turbulence generated either by an oscillating grid, shaken flasks, bubble plumes, or other mechanisms. These devices create environments that are very different from the types of water movement experienced by larvae in nature. For example, laboratory experiments typically aspire to homogenous turbulence, while turbulence in nature (or in the diffuser jet!) is not homogenous. Furthermore, the laboratory experiments typically involve exposing the larvae to some level of turbulent intensity for a period of time, usually much longer than the expected length of exposure in the diffuser jet. For example, many of the experiments expose larval or adult organisms to shear stress for an hour per day, as opposed to seconds in the jet. The shortest exposure time in the laboratory is two minutes (Mead and Denny, 1995). In the one field assessment reported by Jessopp (2007), the velocities measured combined with distances (from Google Earth) indicate the exposure to damaging turbulence in the natural tidal rapids investigated is probably on the order of minutes rather than seconds.

4.2 Review

The effects of turbulence vary with species and with size of organism. Small-scale (< 1 cm) turbulence can accelerate development rates of marine copepods in microcosms (Oviatt 1981; Alcaraz et al. 1988; Saiz and Alcaraz 1991), increase excretion rates (Saiz and Alcaraz 1992a), and modify copepod activity and behavior (Costello et al. 1990; Saiz and Alcaraz 1992c). However, this enhancement of highly expensive motor activity (i.e. higher frequency of feeding bouts and escape reactions, Marrase et al. 1990; Saiz and Alcaraz 1992c) can increase copepod metabolic rates. The increased energy expenditures can lead to decreased growth rates, even if development is accelerated (Peters and Marrasé 2000). Other effects (at higher energy dissipation rates) include abnormal fertilization and development (Mead and Denny 1995) and increases in mortality (Rehmann et al. 2003; Maldonaldo and Lutz 2011).

In general, turbulent eddies that are much bigger than the larvae merely transport them, without affecting them adversely. Smaller turbulent eddies could increase mortality, since velocity gradients exist on a scale small enough to affect the larvae (Rehmann 2003). Thus, very small gametes probably escape damage, as do perhaps large organisms with tough integument. Fish and other larvae on the mm-cm scale may well be susceptible to damage. However, the probability of exposure to the smallest-scaled, most energetic turbulence at the jet centerline is likely to be low.

It is important to be aware that temperature, oxygen content, salinity, alkalinity, and vertical mixing are all factors that affect mortality in addition to the effects of turbulence (Eilav et al. 2002, Danoun 2007). None of the experiments considered any, let alone all, of these additional, possibly synergistic, sources of mortality. It would be advisable to invest in experiments that more closely reproduce the likely experience of entrained larvae. This would help the community to more accurately assess probable outcomes.

REFERENCES

Abrahams, M & M. Kattenfeld (1997). The role of turbidity as a constraint on predator-prey interactions in aquatic environments. Behav Ecol Sociobiol 40: 169 – 174

Alcarez, M., E. Saiz, & A. Calbet. (1994). Small-scale turbulence and zooplankton metabolism: Effects of turbulence on heartbeat rates of planktonic crustaceans. Limnol. Oceanogr., 39(6), 1994, 1465-1470

Bickel, S. L., J. D. M. Hammond, & K. W. Tang (2011). Boat-generated turbulence as a potential source of mortality among copepods. Journal of Experimental Marine Biology and Ecology 401: 105–109

Bruton, M. N. (1985). The effects of suspensoids on fish. *Hydrobiologia* 125: 221-241.

California EPA (2012). Water quality control plan: ocean waters of California

Chesney, E. J., Jr (1989). Estimating the food requirements of striped bass larvae *Morone saxatilis:* effects of light, turbidity and turbulence. Mar. Ecol. Prog. Ser. Vol. 53: 191-200.

Dauvin, J.-C. and J. J. Dodson (1990) Relationship between feeding incidence and vertical and longitudinal distribution of rainbow trout larvae (*Osmerus mordax*) in a turbid, well-mixed estuary. Mar. Ecol. Prog. Ser. Vol. 60: 1-12.

Davis, H. C. (1960) Effects of turbidity-producing materials in sea water on eggs and larvae of the clam Venus (Mercenaria) mercenaria. Biol. Bull.

Einav, R., K. Hamssib, D. Periy (2002). The footprint of the desalination processes on the environment. Desalination 152 (2002) 141-154

Environmental Protection Agency (1988). Turbidity. Water Quality Standards Criteria Summary: A Compilation of State/Federal Criteria. EPA 440/5-88/013

Evans, M. S. (1981). Distribution of zooplankton populations within and adjacent to a thermal plume. Can. J. Fish. Aquat. Sci. 38: 441-448.

Huang, S., N. Voutchkov, S. C. Jiang (2013). Investigation of environmental influences on membrane biofouling in a Southern California desalination pilot plant. Desalination 319: 1–9

Jessopp, M. J. (2007) The quick and the dead: larval mortality due to turbulent tidal transport. J. Mar. Biol. Ass. U.K. 87, 675-680.

Jones, I. S. F. & Y. Toba [EDS.]. (2001) Wind stress over the ocean. Cambridge Univ. Press.

Juhl, A. R., V. Velasquez, M. I. Latz (2000) Effect of growth conditions on flow-induced inhibition of population growth of a red-tide dinoflagellate. Limnol Oceanogr 45:905–915

Juhl, A. R., V. L. Trainer, M. I. Latz (2001) Effect of fluid shear and irradiance on population growth and cellular toxin content of the dinoflagellate *Alexandrium fundyense.* Limnol Oceanogr 46: 758–764

Kiørboe, T., E. Saiz (1995) Planktivorous feeding in calm and turbulent environments, with emphasis on copepods. Mar Ecol Prog Ser 122: 135–145.

Lai, C. C. K. and J. H. W. Lee (2012). "Mixing of inclined dense jets in stationary ambient." Journal of Hydro-Environment Research 6(1): 9-28.

Latz, M.I., J. Allen, S. Sarkar, J. Rohr (2009) Effect of fully characterized unsteady flow on population growth of the dinoflagellate *Lingulodinium polyedrum*. Limnol Oceanogr 54:1243–1256.

Loosanoff, V. L., & F. D. Tommes. (1948). Effect of suspended silt and other substances on rate of feeding of oysters. Science, 107: 69-70.

Lunz, R. G. (1938). Part I. Oyster culture with reference to dredging operations in South Carolina. Part II. The effects of the flooding of the Santee River in April 1936 on oysters in the Cape Romain area of South Carolina. Report to U. S. Engineer Office, Charleston, South Carolina, 1-33.

MacKenzie, B. R. and T. Kiørboe (1995). Encounter rates and swimming behavior of pause-travel and cruise larval fish predators in calm and turbulent laboratory environments. Limnol. Oceanogr., 40(T), 1995, 1278-1289.

MacKenzie, B. R. and T. Kiørboe (2000). Larval fish feeding and turbulence: A case for the downside. Limnol. Oceanogr., 45(1), 2000, 1–10

Maldonado EM, Latz MI (2011) Species-specific effects of fluid shear on grazing by sea urchin larvae: comparison of experimental results with encounter-model predictions. Mar Ecol Prog Ser 436:119-130

Marti, C. L., et al. (2011). "Near-Field Dilution Characteristics of a Negatively Buoyant Hypersaline Jet Generated by a Desalination Plant." Journal of Hydraulic Engineering 137(1): 57-65.

Mead, K. and M. Denny. (1995). Effects of hydrodynamic shear stress on the fertilization and early development of the purple sea urchin, *Strongylocentrotus purpuratus*. *Biol. Bull.* 188: 46-56.

Miner JG, Stein RA (1996) Detection of predators and habitat choice by small bluegills: effects of turbidity and alternative prey. Trans Am Fish Soc 125:97±103

Peters F, C. Marrasé (2000). Effects of turbulence on plankton: an overview of experimental evidence and some theoretical considerations. Mar. Ecol. Prog. Ser. 205: 291–306,

Rehmann, C. R., J.A. Stoeckel, and D.W. Schneider (2003a). Effect of turbulence on the mortality of zebra mussel veligers. Can. J. Zool. 81: 1063–1069

Roberts, P. J. W., et al. (1997). "Mixing in Inclined Dense Jets." Journal of Hydraulic Engineering 123(8): 693-699.

Roberts, P. J. W. and Abessi, O. (2013). “Optimization of Desalination Diffusers Using Three-Dimensional Laser-Induced Fluorescence,” Quarterly Progress Report Number 7, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332, Prepared for United States Bureau of Reclamation, Agreement Number R11 AC81 535, August 14, 2013

Saiz, E., T. Kiørboe (1995). Predatory and suspension feeding of the copepod Acartia *tonsa* in turbulent environments. Mar. Ecol. Prog. Ser. 122: 147-158

SCCWRP (2012), Management of Brine Discharges to Coastal Waters Recommendations of a Science Advisory Panel," submitted at the request of the State Water Resources Control Board by the Southern California Coastal Water Research Project, Costa Mesa, CA, Technical Report 694, March 2012

Vinyard, G. L. and W. J. O'Brien (1976) Effects of Light andTurbidity on the Reactive Distance of Bluegill (*Lepomism acrochirus*) J. Fish. Res. Board Can. 13:2845-2849.

Webster, D. R., et al. (2001). "Simultaneous DPTV/PLIF measurements of a turbulent jet." Experiments in Fluids 30: 65-72.

Wygnanski, I. and H. E. Fiedler (1969). "Some Measurements in the Self-Preserving Jet." Journal of Fluid Mechanics 38(3): 577-612.

APPENDIX A. BIOLOGICAL IMPACTS OF TURBULENCE AND SHEAR STRESS

A summary of laboratory investigations on the effect of turbulence on organisms is shown in the following table.

Summary of lab and field data (and some models) regarding the effects of turbulence on organisms entrained in fluid

Organism	**Shear stress or turbulence**	**Method of generating shear/turbulence**	**Magnitude of critical shear/turbulence**	**Effect**	**Reference**	**Additional notes**
Sea urchin S. purpuratus larvae (3 day; prism)	Laminar shear	Couette flow [1], short term (30 min)	No deleterious effect with $\varepsilon \leq 1$ cm^2/s^3	Change in prey encounter rate	Maldonaldo and Latz (2011)	Neg eff cd be due to erosion of hydromech signal, or if local velocity faster than catch speed, reaction time. Mortality was 19% for the 0.1 cm^2/s^3, 22% for the 0.4 cm^2/s^3, and 53% for the 1 cm^2/s^3 flow treatments compared to 5% for the still control.
		Couette flow Long term (8 days of 12 h on, 12 h off)	$\varepsilon < 0.1$ cm^2/s^3	Excessive mortality		
Sea urchin L. pictus larvae (3 day, 4 arm pluteus)	Laminar shear	Couette flow [1], short term (30 min)	No deleterious effect with $\varepsilon \leq 1$ cm^2/s^3	Change in prey encounter rate	Maldonaldo and Latz (2011)	
		Couette flow Long term (8 days of 12 h on, 12 h off)	No deleterious effect with $\varepsilon \leq 1$ cm^2/s^3	Some mortality, but not much		
Sea urchin *S. purpuratus*	Shear stress	Couette flow (short term: 2 min)	No deleterious effect with $\varepsilon < 200$ cm^2/s^3	Fertilization and development to blastula	Mead and Denny 1995, Denny, Nelson and Mead 2002	

Organism	**Shear stress or turbulence**	**Method of generating shear/turbulence**	**Magnitude of critical shear/turbulence**	**Effect**	**Reference**	**Additional notes**
Zebra mussel *Dreissena polymorpha* veliger	turbulence	Bubble plume for 24 hours, then 24 feed before mortality measured	Mortality increases when d* > 0.9 (eddy similar in size to larva (no sig eff when d*<0.9)	mortality	Rehmann et al. 2003	
dinoflagellate *Alexandrium fundyense*	Laminar shear	Couette flow for 1-24 hours/day	Shear stress τ = 0.003 N/m^2 ; ε = 10^{-5} cm^2/s^3 ; only 1 level	Growth rate decreased when exposed to τ for more than 2 hours/ day	Juhl et al. 2001	Growth rate = 0 when shear 12 h/d; negative when 16-24 h/day
dinoflagellate *Alexandrium fundyense*	Laminar shear and turbulence	Couette flow 1h/d 5–8 d and shaken flasks	Shear stress τ = 0.004 N/m^2 (not quantified for shaken flasks	Growth rate decreased in both	Juhl et al. 2000	Most sensitive last hour of dark phase, under lower light conditions
dinoflagellate *Lingulodinium polyedrum.*	Shear (steady and unsteady)	Couette flow; constant or changing speeds/direction; 2 h/d (change ev 2 min)	smallest ε = 0.04 cm^2/s^3; all had effect (very very high)	Growth rate decreased in all cases; often catastrophically (near 100%)	Latz et al. 2009	Unsteady flow had more of an effect than steady, even when mean was lower; poss mechanism: mechanical energy of the flow alters membrane biophysical properties, activates signal transduction pathway involving GTP, [ca2+]I, poss. Also involves cyclin-dep kinases, as in endothelial cells

Organism	**Shear stress or turbulence**	**Method of generating shear/turbulence**	**Magnitude of critical shear/turbulence**	**Effect**	**Reference**	**Additional notes**
copepod *Acartia tonsa*	Turbulence	model	Starts dropping at $\varepsilon = 10^{-3}$ cm^2/s^3	Decrease in prey capture success	Kiørboe and Saiz 1995	Copepods that set up feeding currents are largely independent of ambient fluid velocity for prey encounters, while ambush-preying copepods can benefit substantially
copepod *Acartia tonsa*	Turbulence	Oscillating grid			Saiz & Kiørboe 1995	
Herring larvae	Turbulence	model	Starts dropping at $\varepsilon = 10^{-3}$ cm^2/s^3	Decrease in prey capture success	Kiørboe and Saiz 1995	
Cod larvae	Turbulence	model	Starts dropping at $\varepsilon = 10^{-5}$ cm^2/s^3	Decrease in prey capture success	Kiørboe and Saiz 1995	
Cod *Gadus morhua* (5-6 mm)	turbulence	Oscillating grid; observations start after 10 min shaking	$\varepsilon = 7.4 \times 10^{-4}$ cm^2/s^3)	Increase in "attack position rate" at all conc	MacKenzie and Kiørboe 1995	Cod benefit more from turb (pause-travel)
Cod *Gadus morhua* (8.7-12.3 mm)	Turbulence -more intermittent	Oscillating grid, observations start after a few min shaking	$\varepsilon = .2, 2 \times 10^{-4}$ cm^2/s^3)	While encounter rate up, pursuit success down	MacKenzie and Kiorboe 2000	Decrease in pursuit success at higher ε; general downward trend with increased rel vel; smaller fish larvae affected more
Herring *Clupea harengus* (8-9 mm)	turbulence	Oscillating grid; observations start after 10 min shaking	$\varepsilon = 7.4 \times 10^{-4}$ cm^2/s^3)	Increase in "attach position rate" only at low conc; v messy data	MacKenzie and Kiorboe 1995	Herring benefit less (cruise)

Organism	**Shear stress or turbulence**	**Method of generating shear/turbulence**	**Magnitude of critical shear/turbulence**	**Effect**	**Reference**	**Additional notes**
Water flea *Daphnia pulex*	turbulence	Vibrating 0.5cm grid	$\varepsilon = 0.05\ cm^2/s^3$ (as compared to calm)	Heart rate increased 5-27%	Alvarez et al. 1994	HR reflects increase in metabolic rate?
Copepod *Calanus gracilis*	turbulence	Vibrating 0.5cm grid	$\varepsilon = 0.05\ cm^2/s^3$ (as compared to calm)	Heart rate increased 93%	Alvarez et al. 1994	Other species too including crab larvae (increase HR 9%)
Copepod *Acartia tonsa*	turbulence	Oscillating grid	$\varepsilon = 0.001\ cm^2/s^3$ (as compared to calm)	Decreases predator sensing ability	Gilbert and Buskey 2005	
Copepod *Acartia tonsa*	Turbulence (field)	Boat wake (field); plankton tow inside/ outside wake	ε =310 cm2 s−3 at a distance of 50 propeller diam. behind 20 mm diam, scale-model boat propeller running at 3000 rpm	More dead inside wake (5-25% increase, over 2-12% background)	Bickel et al. 2011	Stain w neutral red
Copepod *Acartia tonsa*		Mini stirrer w paddles (lab)	$\varepsilon = 0, 0.035, 1.31, 2.24\ cm^2/s^3$		Bickel et al. 2011	$\varepsilon = 0.035\ cm^2/s^3$ did not show negative effect

Organism	**Shear stress or turbulence**	**Method of generating shear/turbulence**	**Magnitude of critical shear/turbulence**	**Effect**	**Reference**	**Additional notes**
various	Turbulence (field)	Rapids (samples collected above and below rapids	ε = 3-742*** cm^2/s^3	Effects dep on species: significant mortality in *Littorina littorea, Mytilus edulis*, and *Aporrhais pespelicant*	Jessop 2007	*Mytilus membranipora, Electra pilosa,* polychaete trochophores and *Lamellaria perspicua* had zero mortality

ε = energy dissipation rate (cm^2/s^3)

Couette flow: two concentric cylinders, outer one rotates shearing volume of fluid between cylinders at known rate

Appendix 2. to Foster et al. (2013)

Comments on Tenera (2012):

"Biological and Oceanographic Factors in Selecting Best Technology Available for Desalination Brine Discharge"

and other turbulence issues

By: Philip J.W. Roberts (italics by Kristina Mead Vetter)

Two separate issues have been raised: The effect of jet-induced turbulence on larvae and entrainment of sediments by the jets.

The Tenera (2012; hereafter Tenera) report repeatedly uses the term "high pressure diffusers." This is not a common term in the field and it is not clear where it comes from. All diffusers are "high pressure" in that the internal pressure is higher than external in order to cause the exit velocity. What does Tenera define as "high pressure?"

The Tenera report consistently mischaracterizes SCCWRP (2012; hereafter SCCWRP), a report from a panel that I chaired, as favoring diffusers. In fact, the Executive Summary of SCCWRP specifically states: "Desirable methods of discharge include co-disposal with heated cooling water from power plants or domestic wastewater, or from a multiport diffuser if "pure" brine is released." The reference to pure brine is for a discharge without co-disposal, and for that case a diffuser is the preferred method. In fact, the major recommendation was that the ultimate salinity increment of salinity over background be less than 5% and that this can be achieved by any combination of in-pipe dilution and near field mixing. No preference was stated for the means to accomplish this level.

The objections to the diffuser and the tenor of this whole issue appears to be Table 1 in Tenera which estimates the additional cost of the diffuser to be $200 million. The report appears to be predicated on the belief that the SCCWRP report prefers a diffuser solution for the Carlsbad plant. This is not the case. The rest of Tenera appears to be an attempt to disparage diffusers.

Tenera contains many inaccurate and misleading statements about SCCWRP, such as:

- Page 3: "The Expert Panel's recommendation to establish a statewide salinity standard of 35 ppt…" The report did not recommend an absolute salinity limit; it recommended an increment over background of 5%.
- Page 3: "The Expert Panel's recommendation to discharge undiluted seawater…" The panel's report did not recommend discharging undiluted seawater. The report actually states: "The preferred methods of discharge are from a multiport diffuser for "raw" effluents, or co-disposal with power plant cooling water or domestic wastewater that results in significant in-pipe dilution." In other words, if undiluted brine is to be discharged, the preferred method of discharge is by means of a diffuser.

Tenera states that "larval fish entrainment losses are theoretically the same for in-plant mixing and offshore diffuser jet mixing…" The "theory" here is merely the report's speculations. There is no theory that says this.

In discussing jet-induced sediment entrainment Tenera states that San Onofre Nuclear Power Plant is California's only large offshore diffuser. This is clearly not true as there are many large diffusers, such as for treated sewage discharges in Los Angeles County. Moreover, the effects of SONGS on turbidity and sedimentation are simply not comparable to a typical brine diffuser. SONGS was designed to rapidly reduce the elevated discharge temperature of over 2,000 million gallons per day of water used to cool the power plant. SONGS diffusers occur along two discharge pipes, each 760 meters long. The diffusers are only angled at 20^0 above horizontal, and also point offshore at 25^0 from the axis of the discharge pipe (MRC 1989). These characteristics are much different from those of the diffusers typically used to dilute brine water and described in Appendix 1.

Tenera states that SCCWRP recommended discharging undiluted seawater that would expose marine organisms to lethal levels of concentrated seawater. In fact, for an efficient diffuser, the high levels would be confined to a very small volume, much smaller than the mixing zones. They only occur on the jet centerlines, and any organisms would be exposed to them for extremely short times (see Appendix 1). The whole concept of a mixing zone is that allowable concentrations can be exceeded within the mixing zone provided they are met at the regulatory mixing zone boundaries, for which an extent of 100 m was suggested by SCCRP.

It is stated that the volume of water affected may be considerable because "…ambient currents would bring a continuous stream of planktonic organisms into contact with the turbulent diffuser field." In fact, for reasons previously stated, only 23-38% of the larvae in this water would likely be affected and only for short times (Appendix 1).

Much of the issue concerns larval mortality due to exposure to shear and turbulence in the jets. While this is certainly a topic of interest, it seems to be overblown. Although the exit velocity in the jets is quite high, this velocity attenuates rapidly with distance from the diffuser to near background level within a few meters. Also, these high velocities occur on the jet centerline and decay rapidly with transverse distance. Therefore, the actual volume of water within which high turbulence and shear occur is very small and close to the nozzles. In addition, the region of high shear at the edge of the jets is confined to the zone of flow establishment, which extends only about six diameters from the nozzles.

Any larvae entrained into the jets will travel along the jet axis and eventually be expelled; at most, they will be exposed to high turbulence levels for tens of seconds. Most larvae will only be exposed to low turbulence levels. The smallest scales of this turbulence are generally smaller than the smallest organisms, suggesting little effect.

Large-scale turbulence (i.e., large eddies) merely transport the larvae. Mortality becomes significant typically when the smallest eddies are about the size of the larvae (Rehmann 2003). Low levels of turbulence can actually facilitate encounter rates (although this does not always lead to increased *feeding, etc.) (*Saiz & Kiørboe 1995, MacKenzie and Kiorboe 1995; details and full references in Appendix 1)

The discussion of diffusers, page 5, is somewhat confused. Tenera conflates momentum and kinetic energy of the discharge. They state that dilution results from the kinetic energy of the source. In fact, for the sewage diffusers that they quote, dilution predominantly occurs due to the buoyancy flux of the discharge, with the momentum being of lesser importance. For a brine (dense jet diffuser) momentum is the predominant driver of mixing.

It should also be noted that there is considerable experience with brine diffusers, especially in Australia. These have been extensively monitored, and show little environmental impact within a few tens of meters from the diffuser. It is not clear why Tenera did not include actual experience with brine diffusers in their report.

As the Tenera report points out, the volume of raw seawater required to reduce salinity of the discharge to a desired level is similar for in-plant mixing or a diffuser. For in-plant mixing with thermal effluent, the diluting water is entrained into intakes; for a diffuser it is entrained into the discharge jets. As the mortality for the intakes is assumed to be 100%, and for a diffuser is always less than this for the reasons stated above, it would appear that diffusers should always result in less mortality. Differences could occur, of course depending on intake and diffuser siting, which could affect where the larvae are entrained from and therefore its composition.

The effect of turbulence on larvae appears to be a function of the turbulence length scales compared to the size of the larvae. The most effect occurs when the two are comparable, especially when the Kolmogorov scale (the smallest scale) is about the same size as the larvae. In a jet, the energy dissipation rates, and therefore length scales, vary considerably along the jet axis and transverse to it. Entrained larvae will be exposed to a range of length scales, only a few of which would cause an effect.

In conclusion, it is my opinion that the arguments against diffusers are primarily motivated by the perception that SCCWRP favors diffusers and that they are being forced on to the Carlsbad plant, at potentially great expense. This is not the case. Tenera goes on to make many “worst-case” assumptions to demonstrate that the co-discharge proposed for Carlsbad is environmentally preferable to a diffuser. While it is true that some damage to larvae may occur due to turbulence in the diffuser jets, it is probable that only a small fraction of those entrained will be subject to damaging levels and for durations long enough to cause significant impact.

<u>Literature Cited</u>:

MRC (Marine Review Committee) 1989. Final Report of the Marine Review Committee to the California Coastal Commission. Document No. 89-02. California Coastal Commission, San Francisco

SCCWRP (Southern California Coastal Water Research Project). 2012. Management of Brine Discharges to Coastal Waters - Recommendations of a Science Advisory Panel. Technical Report 694 to the State Water Resources Control Board, Southern California Coastal Water Research Project, Costa Mesa, CA.

Tenera (Tenera Environmental). 2012. Biological and Oceanographic Factors in Selecting Best Technology Available for Desalination Brine Discharge. Tenera Environmental, San Luis Obispo.

Appendix 3 to Foster et al. (2013)

Comments on Jenkins (2013):

"Dilution Issues Related to Use of High Velocity Diffusers in Ocean Desalination Plants: Remedial Approach Applied to the West Basin Municipal Water District"

By: Philip J.W. Roberts

This report by Jenkins (2013; hereafter Jenkins) suggests a remediation design to the diffusers proposed for the West Basin seawater desalination plant to reduce potential mortality to fish larvae entrained into the brine discharge jets. I have numerous differences and issues with this report.

First, it is not clear why the authors feel compelled to revise the initial design to reduce larval mortality as there is presently no criteria or requirement to address this issue.

The author has assumed design criteria to minimize mortality in the jets that are: Maximum velocity < 1 m/s; shear rate across the jet du/dr < 100 sec^{-1}, and Kolmogorov turbulence length scales significantly smaller than the size of the predominant organisms. It is not clear in the cited references where these specific recommendations appear. The criteria are based on those estimated for hydroelectric turbines and are based on freshwater fish survival; no evidence is presented to show that similar criteria apply to marine larvae in jets. The experiments on which the criteria are based consisted of injection of juvenile freshwater fish into the zone of flow establishment close to the nozzle at the edge of the jet where shear rates are much higher. This is a quite artificial situation for actual fish behavior, which would not be expected to enter this zone. The length of the zone of flow establishment is very short, about six nozzle diameters, and the length of the region where the high shears were exhibited was even shorter. Therefore, the volume of water where marine organisms would be exposed to high shear forces is a very small fraction of the mixing zone.

Of more concern is the proposed change in design to the brine diffuser. Basically, the jet exit velocity is reduced to satisfy the arbitrary criteria that are assumed. This reduction in velocity, and in the densimetric Froude number of the jet, reduces dilution and it is assumed that dilution is increased by increasing the turbulence intensity prior to discharge. Turbulence intensity is increased by two methods: a "swirl chamber" with a rapid internal expansion that generates turbulence by shear, and internal helical ribbing that produces swirl.

The number of nozzles is increased to four per riser in a "Rosette" design (referred to as Rosseta in the report). This is a commonly used design, for example, Sydney, Australia, but the jet velocities in the proposed design are too low for effective dilution.

There is little basis for the assumption that dilution is increased by increasing turbulence in the jet prior to discharge. Dilution is produced by entrainment by the larger eddies at the jet edges which are in turn generated by the mean shear in the jet. Internal turbulence will have little effect on this entrainment and therefore dilution; the role of the internal turbulence is primarily to mix already entrained water in the jet.

The "GHD design" is similar to what is used in the Sydney, Australia, brine diffusers. But this was not designed to be a "swirl chamber," in fact, physical modeling was undertaken at the University of New South Wales to minimize swirl and head loss. Even if internal turbulence was shown to be a significant effect, it is not clear why this complicated design would be used; instead it would be simpler to increase the internal roughness of the diffuser nozzles to increase turbulence intensity levels.

The justification for the new design and effect of turbulence levels is not convincing. The author has used commercial CFD software to model the jets. No validation of the models is presented, no evidence that this software has been successfully used for similar dense jet problems, and no comparisons with experimental data or other calculation procedures are presented to justify use of the models. Indeed, the report has little context or acknowledgment of the extensive work that has been conducted on dense jets and brine diffuser designs.

It is claimed that an improvement in the proposed design is that the jets will not impact the water surface. This is primarily because of the reduced exit velocity and densimetric Froude number of the jets, but the same result could be effected by reducing the nozzle discharge angle, as extensive experimentation has shown that dilution is not sensitive to the nozzle angle over quite a wide range of angles.

It is stated that dilution is not as good as the present ARCADIS design but will still meet the proposed 5% criteria. This implies that the present diffuser is over designed, and the nozzle diameter could be increased, reducing the jet exit velocity and shear and turbulence effects.

Figure 1.1, that appears to show streamlines for a jet-induced flow, is not convincing as the streamlines are parallel to the jet axis, rather than diverging as would occur in an actual jet. Similar patterns are observed in Figure 4.4, and Figure 4.5 appears to show a leveling off of the jets after the terminal rise height rather than a descent to the seabed that would actually occur.

The densimetric Froude number of the modified diffuser design is about 4. This is a weak jet of insufficient strength to ensure that the proposed salinity requirement will be met and the arguments that increased turbulence in the jets will ensure that the requirement will be met are not convincing.

A Vortex Lattice CFD model is applied to predict the kinetics of the discharge plume, although little information is provided on grids, solution methods, etc. to judge it.

Figure 4.6 shows turbulent length scales in the turbulent mixing zone. This graph is puzzling. It is not stated where the computations are made, or what is meant by "aggregate turbulent mixing zone." What is *y* and *H*? Are they on the jet centerlines, and how far from the nozzle? The figure appears to be incorrect, as it shows energy peaking at the Kolmogorov scales, rather than the larger eddy sizes, and in a jet, the largest (energy containing) eddies vary along and across the jet and are about an order of magnitude less than the total jet width. According to the caption, f(η) is dimensionless, but on the graph scale, it has units of cm^2/s^2. Which is it? Why is the peak identified with the Kolmogorov scale? Why doesn't the autocorrelation go to unity as the length scale tends to zero? What are the subscripts *i* and *j*? If the cumulative curve is the area under the distribution curve, why do they have the same units? It is stated that 99% of the turbulent energy in the "aggregate mixing zone" occurs at scales smaller than 1.5 mm. This cannot be correct, as most of the energy is contained in eddies that are of order of the jet width, which is much larger than 1.5 mm.

Figure 4.7 shows Visual Plumes simulations, presumably with the model UM3. The graph is used to show that the proposed design will meet the proposed water quality requirement. However, this model assumes that all the turbulence in the jet is generated by the jet itself, and dilution is due to entrainment by this turbulence. This contradicts the authors' assumption that "pre-mature" turbulence is needed in the jet to meet the water quality requirement, and indeed the whole concept of the swirl diffuser. However, as stated earlier, comparisons with experimental data indicate that the proposed design will not meet the dilution requirement at the low Froude numbers proposed.

It is stated that exposure times of drifting organisms to very high salinity levels for the proposed revised diffuser designs are longer than the original design. It is stated that these times are of order 1 hour for exposure to salinities greater than 45 ppt. It is not clear how these numbers were arrived at. An actual diffuser will achieve very rapid dilution and attenuation of salinity in the jet with more realistic exposure times of the order of seconds.

Figure 1.2 purports to show that the high velocity core is relatively narrow and extends 3 to 5 diameters from the nozzle. This conclusion cannot be derived from this figure, which only applies to the zone of established flow beyond the zone of flow establishment, which is presumably what is meant by high velocity core. It is also not clear what is meant here: the jet centerline velocity is approximately constant for a distance along the jet axis of about six nozzle diameters, but the report refers to *lateral* dimensions. It is not explained how the equation for the mean rate of shear is computed.

In summary, it is my opinion that Jenkins uses unproven models to predict the behavior of the turbulent jets; that the concept of reducing velocity and shear but compensating by increased turbulence levels prior to discharge is unproven and unlikely to be effective; that the report has no context within the extensive research that has been conducted on dense brine diffusers; that the reduction in jet exit velocity, and consequently jet Froude number, will reduce dilution to the point where it is unlikely that the proposed dilution criteria will be achieved; and the criteria assumed are not proven. The concept of designing so that the smallest scale is smaller than the smallest larvae sizes is also questionable. Because of the spectrum of eddy sizes, there will always be eddies of size comparable to the larvae size. The turbulence scales in the original design will also be smaller than the smallest length scales, and the mean shear will also fall with the authors' criteria. The only criteria that would not be satisfied is the jet exit velocity, which, as previously discussed is arbitrary. The reduction in the jet velocity of the revised design results in a weak jet with low Froude number which is unlikely to satisfy the proposed design criteria. The report is well out of the mainstream of established engineering design and diffuser technology.

For the reasons discussed above, the recommendations in Jenkins and the modified design should be undertaken with considerable caution.

Literature cited:

Jenkins, S.A. 2013. Dilution Issues Related to Use of High Velocity Diffusers in Ocean Desalination Plants: Remedial Approach Applied to the West Basin Municipal Water District Master Plan for Sea Water Desalination Plants in Santa Monica Bay. Scott A. Jenkins Consulting, Poway.

Appendix 4. to Foster et al. (2013)

Review and Responses to Questions Concerning APF and Mitigation Fees

By: Peter Raimondi

Questions related to Foster et al. (2012) and related discussions:

1) how the mitigation fee was calculated and the use of APF versus other possible economic models,
2) the application of APF to intakes where entrainment studies have not been done,
3) how to adjust APF for entrainment reduction using screens and other devices.

To answer these questions as well as comment on WBMWD (2013) I will first provide more detailed information about the APF model. The following text (italicized) is taken in part from Steinbeck et al. (2007).

Area of Production Foregone (APF) *models (sometimes also called Habitat Production Foregone; HPF) can be used to understand the scale of loss resulting from an impact and the extent of mitigation that could yield compensation for the loss. It is based on the idea that losses from environmental impacts can usually only be estimated from a group of species and that the true impact results from the sum of direct and indirect losses attributable to the impact. The use of APF allows for the estimation of both the direct and indirect consequences of an impact and provides a currency (i.e., habitat acreage) that may be useful for understanding the extent of compensation required to offset an impact.*

Probably the most controversial issue in APF assessment is how it treats the few taxa actually analyzed in the assessment. In most assessments, including ***Habitat Replacement Cost (HRC)*** *(Strange et al. 2004), estimates of loss of taxa are implicitly considered to be without error. In APF, each estimate is considered to be prone to (sometimes) massive error (indeed, estimates of confidence intervals in ETM calculations often cross through zero). In APF models the assumption is that each taxon represents a sample and that the mean of the samples is representative of the true loss rate. For example, assume 5 taxa and the ETM calculations indicate that for an estuarine system of 2000 acres the loss rates for the 5 taxa are 5, 10, 3, 22 and 15 percent. In APF the estimate of likely loss would be the average of the 5 values or 11 percent. Because APF considers taxa to be simply independent replicates useful for calculating the expected impact, the choice of taxa for analysis may differ from HRC assessments. In APF the concern is more that each taxon is representative of other taxa that are either unsampled (most invertebrates, plants and holoplankton) or not analyzed (the vast majority of fish). In APF, the average loss across taxa then represents the average loss across all entrained organisms. This is a fundamental difference between APF and economic based models like HRC.* ***The underlying statistical-philosophic basis of APF addresses one of the most problematic issues in impact estimation: the typical inability to estimate impacts for unevaluated taxa.***

In APF, the next step is to take the average loss rate and turn it into an ecological currency, which then can be used to understand the impact and form a basis for mitigation. Almost always the loss rate is based on an Empirical Transport models (ETM), although APF approaches can be used with other loss models such as Fecundity Hindcast (FH) or Adult Equivalent Loss (AEL) models. The main reason for the use of ETM approaches is that FH and AEL models rely on detailed life history information (including early survivorship), which is often unknown or variable for focal species. Such information is not required for ETM. Calculation of ecological currency can be quite a simple step. Loss is turned into habitat from which production is foregone. This is calculated as the area of habitat that would need to be added to the system to make up the lost resources. The APF model stems for the ETM calculation as shown below. Note that this is essentially a compound interest calculation.

$$P_m = 1 - \sum_1^n f_i \quad (1 - PE_i)^d \qquad \text{(1)}$$

Where

f_i is the proportion of total larvae entrained in a year, entrained in period i
PE_i is the estimate of proportional entrainment (proportion of vulnerable population lost per day) for period i
d is the number of days that larvae are exposed to entrainment

Here the assumption is that the source water body (SWB) is constant and completely sampled. If this is not the case the calculation is somewhat more complex. APF then is simply:

$$APF = \overline{P_m}\ x\ SWB \qquad (2)$$

Using these calculations and the example above, the estimate was that 11% of organisms at risk in a 2000¬acre estuary were lost to entrainment. The estimated loss (11%) would have been calculated as the average of the species specific proportional mortality (P_m) rates calculated using empirical transport modeling. The estimate of APF then would simply be 2,000 acres (SWB) x 11% or 220 acres.

Therefore the creation of 220 acres of new estuarine habitat would compensate for the losses due to entrainment. This does not mean that all biological resources were lost from an area of 220 acres, which is a common misunderstanding. Instead it means that if 220 acres of new habitat were created, then all losses, calculated and not calculated, would likely be compensated for. Here again is an important feature of APF. The currency of impact (acres needed to compensate) includes all impacts, even indirect ones. One common criticism of the approach of focusing more detailed analysis to only a limited number of taxa is that not only are other taxa directly affected by entrainment not assessed, but that there is also no provision for estimation of indirect impacts (often food web considerations). APF addresses this concern by expressing impact in terms of habitat and assuming that indirect impacts are addressed by the complete compensation of all directly lost resources. This is quantitatively impossible using traditional economic approaches in the HRC family of models.

In the given example, APF would predict that the creation of 220 acres of new habitat would compensate for all impacts due to entrainment. What sort of habitat should be created? Again the statistical-philosophic basis of APF contributes to the answer. Because taxa in APF are simply independent replicates that yield a mean loss rate, habitat is not directed by taxa. Instead the approach assumes that habitat should be created that represents the habitat for the populations at risk. If the habitat in the estuary was 60% subtidal eelgrass beds, 15% mudflats and 25% vegetated intertidal marsh, then these same percentages should be maintained in the created habitat. Doing so would ensure that impacts on all affected taxa would be addressed.

The logic of the example would seem to imply that this methodology would only be useful if there were habitat creation opportunities. However even if there are not local opportunities, the approach is useful for other reasons:

1) Opportunities may exist in other locations (such as another nearby estuary);

2) Area of Production Foregone can be useful in understanding the scale and relative importance of the impact, which helps with permitting decisions, and in establishing a cost-basis for the impact; and

3) Often there are alternative mitigation strategies that could be implemented whose scale would be determined by APF. An example would be the size of the creation of an artificial reef or the area of a marine reserve designated as mitigation for entrainment losses.

Question 1: How the fee was calculated and the use of APF versus other possible economic models
The simplest calculation of the fee was based upon the real or estimated cost of mitigation using APF calculation and the volume of water entrained. It is essential to note APF modeling produces a range of values (acres), each representing a degree of confidence that the resultant mitigation will be compensatory. The decision of amount of acreage (and as a result, the likelihood of full compensation) is made by the group (board, commission, etc.) that has permitting authority. The cost of the mitigation is then divided by the volume of entrained water to produce a cost per unit volume of water. The metric relies on the assumption that marine resources lost due to entrainment are correlated in a linear fashion with the volume of water used. This is called the volumetric assumption. This has been examined in a number of cases and is generally true in large part due to the use of ETM, which is based on proportional rather than numeric vulnerability. The other part of the fee calculation is the estimate of cost per unit area for mitigation projects. Here there appears to be an effect of type of mitigation project. In particular, wetland creation and restoration (which maybe reasonable for an estuarine or soft-bottom open coast intake) has been more expensive per acre than reef creation (which would be used for an open coast rocky bottom intake). The fee could be adjusted to reflect such differences (as noted in the original document).

Use of APF for assessing impacts and mitigation has been, to my knowledge, universal in 316(b) or 316(b)- like considerations for over a decade in California. There are a series of reasons for its use versus other models such as HRC models. First, APF as implemented has relied entirely on Empirical Transport modeling, which produces estimated of proportional mortality of larvae. Importantly, this means that estimates of adult loss are unnecessary. This is essential because we have little information about survivorship rates of most California fish during their egg and larval periods, which is required to produce estimates of adult stock lost. HRC relies on assessment of adult loss, and if survivorship data re unavailable for certain species, the HRC calculations can have large standard errors associated with the values and become unreliable. Second, as implemented, APF can be used in data poor situations – these are studies where only a small fraction of species entrained are assessed, which is always true for entrainment studies. This attribute of APF is due to two factors: (1) species assessed are chosen to be robust estimates representative of classes of species entrained (not true in HRC), and (2) compensatory mitigation is calculated based on being representative of habitat utilized by *all* entrainable species. Hence, successful mitigation will compensate for all species affected by entrainment via direct or indirect pathways. By contrast the outcome of HRC assessment is typically species specific mitigation recommendations, which as discussed above will not cover the vast number of entrained species not assessed nor those affected indirectly (e.g. a species that is not entrained but which consumes one that is).

Question 2: The application of APF to intakes where entrainment studies have not been done
The math of the ETM as applied to entrainment studies in California is such that, in theory, volumetric estimation (see above) could be very similar to that produced using biological estimation. This link is conditional because it relies on patterns of larval species distribution and concentration being similar in intake and source water body (SWB) water masses. It is essential to note that the actual concentration of larvae is unimportant to the calculations. Fortunately there have been a series of studies where biological assessments have been done and can be compared to volumetric assessments. Generally there has been a good and unbiased match between the two methods. Given this a volumetric approach could be used for at least four situations: (1) where the intake volumes are low. Here the idea would be to estimate the value of the lost resources without spending a lot on the study. (2) For larger intakes where the duration of the impact is short (e.g. for a power plant that will be going to close cycle cooling in 5 years). (3) For larger intakes prior to a biological assessment. (4) For moderate intakes where parties agree to abide by the volumetric approach (e.g., desalinization operations)

The table below shows a volumetric approach applied to power plant intakes where mitigation cost were either estimated or documented. In all cases the mitigation was considered compensatory and was based on the ETM-APF approach. The cost of the mitigation was then re-calculated on a volumetric basis [$$$ per Million Gallons per Day (MGD) of intake]. Four examples of wetland mitigation and one example of rocky reef mitigation are shown and for the four cases of wetland mitigation the cost of mitigation per million gallons of daily intake are remarkably constant and average $38,520. The cost per million gallons of daily intake for an artificial reef project is considerably less, $25,421, reflecting in part the difference in land costs. It is important to state the implications of this analysis – for intakes primarily affecting wetland species, or where wetland creation or restoration is the preferred mitigation option, compensation can be attained for an average of $38,520 per million gallons of daily intake of water. The same is true (for a lesser amount) if the mitigation option is a rocky reef.

Facility	Intake Volume (MGD)	APF (acres)	Mitigation Type	Cost estimate	basis year	cost per daily intake (MG)	Notes
Moss Landing Combined cycle	360	840	wetland	$15,100,000	2000	$41,944	based on max larval duration, dollars in year 2000
Morro Bay	371	760	wetland	$13,661,905	2001	$36,825	based on max larval duration, dollars in year 2001 and cost per acre = Moss Landing)
Poseidon	304	37	wetland	$11,100,000	2009	$36,513	based on max larval duration, dollars in year 2009 and cost per acre =300K (SONGS cost)
Huntington Beach	127	66	wetland	$4,927,560	2009	$38,800	based on max larval duration, dollars in year 2009 and cost per acre =74.66K (from Davis et al report and final permit (acres)
Diablo	2,670	543	Rocky reef	$67,875,000	2006	$25,421	based on125K per acre (SONGS) in 2006
						$38,520	Average (wetland mitigation)
						$25,421	Rocky reef mitigation

Question 4: How to adjust APF for entrainment reduction using screens and other devices.
Using the RTM/APF approach this is straight forward. Recall that

$$APF = \overline{P_m}\ x\ SWB$$

And that

$$P_m = 1 - \sum_1^n f_i \quad (1 - PE_i)^d$$

For this question the key variable is PE – proportional entrainment. This is the proportion of larvae that are vulnerable which are lost to entrainment per day. Assume that PE is 0.1, that is, there is a 10% risk of entrainment. Further assume that we know from studies that 85% of larvae that would be entrained are precluded from entrainment if wedge wire screening (of some gap dimension) are used. In this example the derived PE would be 0.1 x 0.15 = 0.015. This value would be substituted into the P_m calculation, which feeds the APF calculation.

This approach will work for any device for which there is an estimate of entrainment reduction. It is essential to recognize that this approach works to correct species specific P_m estimation, but that this may compromise the assumption that the species used to calculate $\overline{P_m}$ are representative of entrained species of interest (all except holoplankton). That assumption is based on an open water intake with no prophylactic devices. Here size does not matter and representation is mainly with respect to larval duration and adult habitat. Once screening is adopted, size becomes an issue primarily because the size distribution of larval invertebrate species is generally smaller than the size distribution for larval fish. Hence, estimation based on reduction of fish larval entrainment would over-estimate the net effect on the species at risk. This can be accommodated by considering the unaffected species separately. One approach would be to use the open intake $\overline{P_m}$ as representative of the unaffected species and the screen estimate of $\overline{P_m}$ as representative of affected species and calculate a weighted average of the two with the weighting being provided by the relative concentrations of each type of species in the water column. This weighted $\overline{P_m}$ would be inserted into the APF calculation, yielding an estimate calibrated to screening effects.

As an example, assume that wedge wire screen has been installed and that that it prevents 50% of all fish larvae from being entrained. However also assume that virtually all other meroplankton that were entrainable are still entrainable (this is a likely situation). Studies that have examined the percent contribution of fish larvae to nearshore meroplankton are rare but fish contribution is below 1% (Byrne 1995). These values can be inserted into the calculations above to see the effect on $\overline{P_m}$. Here, instead of using species as replicates (as is generally done), the use of screening requires that $\overline{P_m}$ be calculated as the weighted average of P_m uncorrected (.99) and P_m corrected (.01) for reduction in entrainment due to screening (the 50% reduction is applied to the exponent (d). The reduction in entrainment mortality under these realistic assumptions is less than 1%.

Comments on the West Basin submission (WBMWD 2013)

I am restricting my comments to the presentation submitted “Intake Entrainment: 5 step calculation” and specifically to the application of ETM to APF for the purpose of determining a mitigation fee. There are a number of questions/issues that need to be addressed prior to a substantive assessment of WBMWD (2013).

The general approach that has been used to calculate APF is discussed above and involves calculation of P_m for multiple species, which allow for the estimation of $\overline{P_m}$, which is considered to be representative for *all* entrained species. Two issues arise when using a single species such as silversides: (1) there is little chance that it will be representative of all species at a given location as assumed in the APF approach, and (2) there is no way to calculate a confidence interval for APF, and a confidence interval gives the ability to link likelihood of compensation to APF estimates. For example, the average APF has a 50% likelihood of providing full compensation for impact entrainment. The APF method was applied and used as the basis for mitigation at Poseidon (another desalination project and used in the West Basin submission as an example). If there is a strong justification for the use of a single species, it should be clearly laid out.

The next issue that needs attention is the calculation of P_m due to screening. As presented in WBMWD (2013), the calculation is incorrect as the reduction was applied directly to P_m when it should have been applied to PE (see equations above).

Finally, a whole-life approach is advocated by West Basin. Essentially this approach is a way to discount younger larvae based on natural mortality rates. The effect is to reduce P_m through disproportionate representation of older, effectively screened individuals. This demographic approach might be suitable if the following could be addressed

1) One of the key strengths of the ETM/APF approach is that it allows compensation for direct and indirect effects dues to entrainment. One tenet of using the ETM/APF method is that a larva is not simply a pre-adult stage. Larvae (and other plankton) form the base of the marine food web, so the larva could also be an edible stage for larger fish or birds. Naturally high larval mortality at the younger stages need not automatically be a basis for discounting, given that the mortality is fueling survival and growth of other species.
2) The calculation of the whole life values is not described in adequate detail and thus is impossible to evaluate.
3) The whole-life approach appears to rely on accurate size specific survivorship rates. The absence of such information for many California coastal species is one of the main reasons ETM is used.
4) If discounting based on whole-life is applied, the discount should first be directly applied to the initial Pm estimates. It is possible that the discount is in the calculation, but because the equations are not shown I can't tell where the discount was applied.
5) It appears that the product of screening effect and the whole-life approach is inappropriate. Again, because the equations are not shown, the basis of the calculation is impossible to assess.

<u>Literature cited:</u>

Byrne, P. 1995. Seasonal composition of meroplankton in the Dunkellin Estuary, Galway Bay. Biology and Environment 95B(1): 35-48.

Foster, M.S., Cailliet, G.M., Callaway, J., Raimondi, P. and Steinbeck, J. 2012. Mititation and Fees for the Intake of Seawater by Desalination and Power Plants. Report to State Water Resources Control Board, Sacramento.

Steinbeck, J.R., Hedgepeth, J., Raimondi, P., Cailliet, G. and Mayer, D.L. 2007. Assessing Power Plant Cooling Water Intake System Entrainment Impacts. California Energy Commission Consultant Report CEC-700-2007-010. California Energy Commission, Sacramento.

Strange , E.D, Allen, D., Mills, D. and Raimondi, P. 2004. Research on estimating the environmental benefits of restoration to mitigate or avoid environmental impacts caused by California power plant cooling water intake structures. California Energy Commission Report 500-04-092, Sacramento.

WBMWD (West Basin Municipal Water District). 2013. Intake entrainment 5 step calculation (illustrated PDF submitted to SWRCB, April 5, 2013). West Basin Municipal Water District, Carson, CA.